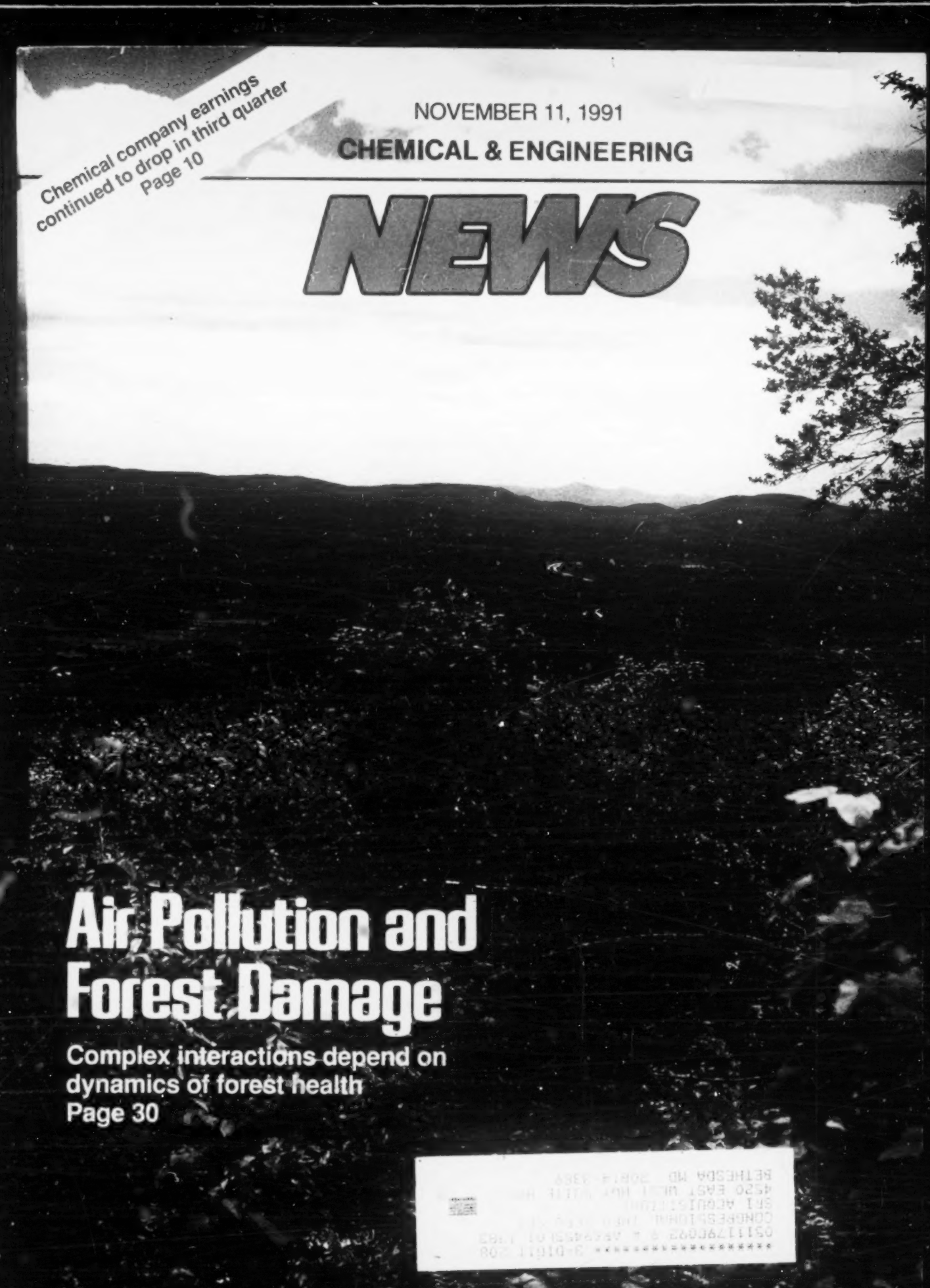
NOVEMBER 11, 1991
CHEMICAL & ENGINEERING

NEWS

Chemical company earnings continued to drop in third quarter
Page 10



Air Pollution and Forest Damage

Complex interactions depend on dynamics of forest health
Page 30

CHEMICAL & ENGINEERING
NEWS
NOVEMBER 11, 1991

Volume 69, Number 45
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News of the Week

■ **In a deal with the White House, Congress has revived the controversial Critical Technologies Institute just two months after the Administration asked that the idea be killed.** **Page 4**

■ **The NMDA receptor, a protein that plays a key role in nerve transmission and in disorders like epilepsy and stroke, has been cloned and characterized in rats by Japanese researchers.** **Page 5**

■ **A record fine of $10 million levied by OSHA will be paid by IMC Fertilizer and Angus Chemical for alleged safety and health violations related to a nitroparaffins plant explosion.** **Page 5**

■ **NSF's advisory committee for chemistry criticizes the new Presidential Faculty Fellows program, fearing politics and prestige will outweigh scientific merit in the selection process.** **Page 6**

Business

Earnings of major chemical companies continued to fall in the third quarter, marking the ninth straight quarter of decline. **Page 10**

Major changes are under way in the pulp and paper industry that will affect consumption of chemicals. **Page 15**

Australian chemical industry faces some tough problems, particularly a very unfavorable attitude from the public. **Page 16**

Government

NSF's chemistry division proves resourceful in creating ways to stretch its grant support as division faces yet another disappointing funding increase. **Page 19**

Science/Technology

New university in Hong Kong aims to offset brain drain and bolster industrial growth as colony faces reintegration into China. **Page 26**

Role of undergraduate research in chemical education is focus of Dutch symposium to be held later this month in Amsterdam. **Page 28**

Spacecraft Magellan yields dramatic views of Venus' landscape, showing volcanoes and craters in three dimensions. **Page 29**

Cover: Northern hardwood forest in Hubbard Brook Experimental Forest, central New Hampshire. Photo by William H. Smith, Yale University

Letters 2

Concentrates
Business 7
Government 18
Science/Technology 25

The Departments
ACS Comment 44
Meetings 45
Awards 59
Newscripts 60

Special Report

Regional air pollution is one of the most significant contemporary stresses on forest ecosystems in the U.S. and Canada. **Page 30**

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LETTERS

Universal symbol

In a letter to the editor (C&EN, Sept. 9, page 2), John Cox urges ACS to attempt to develop a generally recognizable generic symbol for "chemicals." ACS has in place a committee dedicated to problems of nomenclature, symbols, and pronunciation; it maintains a close liaison with the International Union of Pure & Applied Chemistry, which is dedicated to such concerns.

Those readers who have thoughts, as well as creative suggestions, pertinent to this concern are invited to send them along to the undersigned member of the ACS committee, or, more appropriately, to the committee's chairman, Peter A. S. Smith, Department of Chemistry, University of Michigan, Ann Arbor, Mich. 48109.

Jack H. Stocker
Department of Chemistry
University of New Orleans
New Orleans, La. 70148

I was appalled by the publication of the letter on a universal symbol for chemicals by John L. Cox . One of ACS's aims is to aid the public in understanding that chemicals are omnipresent and are not found only in laboratories, factories, and toxic waste dumps. A request by a single fellow ACS member for a "universally recognized chemical symbol" is surprising, but seeing it in print in this magazine makes one wonder if the educational process needs to begin in our own ranks.

Fred C. Frederick
Roanoke, Va.

Licensing chemists

I must respond to, and rebut, many of the points raised in William A. Levinson's letter (C&EN, Aug. 19, page 5) regarding licensure of chemists. The public's perception of the benefits and detriments of materials, drugs, and chemicals combined, is based on ignorance, hearsay, and sales pitches. Drugs for chemotherapy are highly potent and are toxic. However, the benefits they offer clearly outweigh their risk—but this does not diminish the care with which they must be handled. All drugs are hazardous if used improperly.

As far as chemicals go, the public is sensitized to chemical spills and hazards, not benefits. The tragedies make the front page. The value to society is rarely a front-page affair. Society expects these benefits as a matter of course. I'm sure that if a new chemical plant, of whatever form or size, were to be sited in my community, the first question asked about the venture would not be in regard to the increased tax base, the number of jobs produced, or the gains to society that could be realized. Rather, it would relate to the toxic effects of plant operations, real or imagined.

The basic distinction between a licensed profession, such as medicine, law, or private engineering, versus an unlicensed profession, such as chemistry, is the concept of private practice. This concept is that of a professional offering his or her services directly to the public at large for a fee. If John Q. Public walks into Dr. X's office, there must be a level of trust between the two, since John Q. is not a doctor. If I, as a chemist, opened an office and hung my degrees on the wall, I would spend most of the day reading *Chemical & Engineering News* and staring at my degrees. There are very few opportunities for me to offer my research services directly to the public. We license truck drivers, because although truck driving does not require an advanced degree, it does require a special set of skills (such as those for certification) and truck drivers may offer their services directly to the public (as independents).

The argument that licensure of chemists would cut industrial costs is absolutely ludicrous. It is analogous to stating that, because doctors are licensed, health care and malpractice costs are contained! I suppose we could set up our own coterie. Then, we could get our salaries up to the level of M.D.s. I see that we already have a large degree of prestige (C&EN, Sept. 2, page 30); perhaps we could raise that as well. By the way, who would cover my malpractice insurance?

Levinson, why do you make the distinction that only chemists "whose jobs affect worker or public safety" be licensed? Who is exempt? Of course, all professors with graduate students must be licensed, since they would be involved with "worker safety." Perhaps we could exempt theoretical chemists, since they don't actually work with com-

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Chemical Earnings, Profitability Tumble Again in Third Quarter

William J. Storck,
C&EN Northeast News Bureau

It has been nine straight quarters of declining earnings for the chemical industry. The third quarter of 1991 continued the story that has been unfolding since the middle of 1989 of declining demand, overcapacity in some areas, and prices that do not necessarily cover costs—especially for those companies that produce large-volume and highly cyclical commodity chemicals.

As a result, earnings for many chemical companies plummeted in the third quarter, bringing the average decline for C&EN's sample of 30 firms to a 13% decrease, when compared with third-quarter 1990. Sales for the companies also fell, as did profitability.

Practically the same pattern was repeated for other companies that are major producers of chemical products. Oil firms reported a big earnings plunge in the third quarter, as did diversified manufacturers that include chemicals in their portfolios. Once again, only the pharmaceutical companies recorded good increases on a year-to-year basis.

And once again, the explanation is easy. The U.S. is in the throes of recession. The result is that demand for chemicals and related products is down in many major U.S. industries, including two of the biggest—housing and automobiles.

Although this, of course, does not affect chemicals across the board, it does have a big impact on the major commodity products, especially petrochemicals. And since petrochemicals are such a large part of the in-

Chemical industry leaders for third quarter . . .

Sales

Rank 1991		$ Millions	Rank 1990
1	Dow Chemical	$ 4502.0	1
2	Monsanto	2042.0	2
3	Union Carbide	1751.0	3
4	W. R. Grace	1621.6	4
5	American Cyanamid	1118.1	5
6	Air Products	738.4	6
7	Hercules	717.0	7
8	Arco Chemical	705.0	9
9	Rohm & Haas	672.1	8
10	B. F. Goodrich	649.5	11

Earnings[a]

	$ Millions	Rank 1990
Dow Chemical	$223.0	1
Monsanto	116.0	3
Air Products	58.4	4
American Cyanamid	56.3	7
Ethyl	55.3	5
W. R. Grace	49.6	10
Rohm & Haas	39.5	9
Great Lakes Chemical	39.2	13
Arco Chemical	35.0	6
Nalco Chemical	34.7	15

Profitability

	Earnings as % of sales	Rank 1990
Loctite	13.7%	3
Great Lakes Chemical	12.2	2
Betz Laboratories	11.7	4
Nalco Chemical	10.0	5
Ethyl	8.9	8
Lubrizol	8.1	6
Air Products	7.9	14
IMC Fertilizer	7.7	9
Georgia Gulf	7.5	7
Crompton & Knowles	7.3	13

. . . and for first nine months of 1991

Sales

Rank 1991		$ Millions	Rank 1990
1	Dow Chemical	$14,244.0	1
2	Monsanto	6,738.0	2
3	Union Carbide	5,359.0	3
4	W. R. Grace	4,971.9	4
5	American Cyanamid	3,851.3	5
6	Hercules	2,219.0	6
7	Air Products	2,206.5	7
8	Rohm & Haas	2,104.7	8
9	Arco Chemical	2,090.0	9
10	Ethyl	1,915.1	13

Earnings[a]

	$ Millions	Rank 1990
Dow Chemical	$821.5	1
Monsanto	555.0	2
American Cyanamid	292.9	4
Union Carbide	169.0	3
Air Products	166.9	6
Ethyl	158.3	8
W. R. Grace	138.0	9
Rohm & Haas	133.6	7
Arco Chemical	120.0	5
Great Lakes Chemical	117.8	11

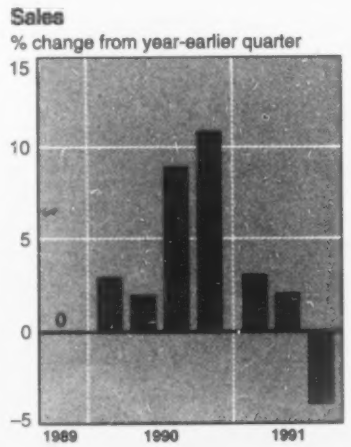
Profitability

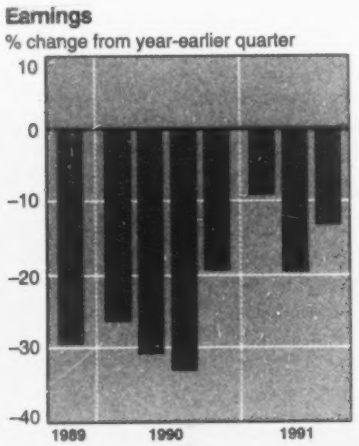
	Earnings as % of sales	Rank 1990
Loctite	13.9%	3
Great Lakes Chemical	12.0	2
Betz Laboratories	11.4	5
Nalco Chemical	10.2	5
Lubrizol	8.3	8
Ethyl	8.3	9
Monsanto	8.2	17
Crompton & Knowles	8.0	10
IMC Fertilizer	8.0	16
American Cyanamid	7.6	15
Air Products	7.6	13

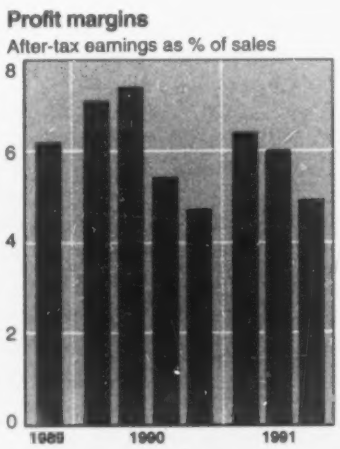
Note: Based on 30 chemical companies listed on page 12. a After taxes.

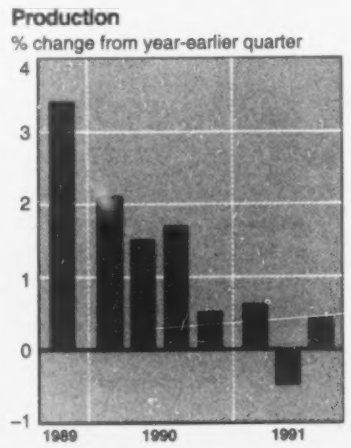
Chemical industry 1991 third-quarter results

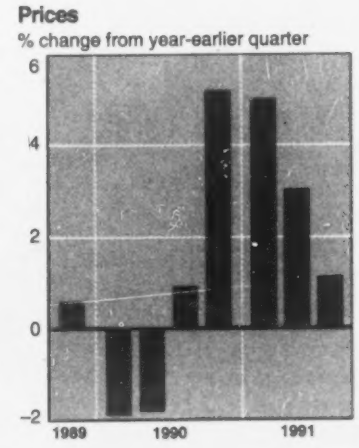
- Sales declined 4%
- Earnings dropped 13%
- Profit margins fell to 4.9%
- Production stayed even
- Prices increased just 1%











Note: All sales, earnings, and profit margin data are based on 30 chemical companies listed on page 12.

dustry, both in terms of physical volume and dollars, the downturn in these products has enormous effects on the fortunes of the entire industry.

As a result of the declining demand for chemicals, capacity use for the industry fell to a seasonally adjusted 78.8% for the third quarter, according to government data, from an average 81.3% in the same period a year earlier. Overall, much of this drop is due to new chemical plants starting up during the intervening period, but in parts of the industry, it includes decreasing demand leading to declining output at chemical plants.

Overall production for all U.S. chemical plants, according to the Federal Reserve Board, was essentially unchanged in the third quarter when compared with the year-earlier period. However, for industrial organic chemicals, the subcategory that contains basic petrochemicals, output was down an estimated 7%.

Falling product demand, and its resulting lower capacity utilization, naturally led to weakening prices in the third quarter. Again, according to government figures, prices for chemicals and allied products rose just 1.1% in the third quarter from the same period last year—well below general inflation in the U.S.

For some subcategories, the picture was bleaker. Prices for industrial chemicals, which include both basic inorganic and organic products, fell an average of 2.1%, according to government data, whereas prices for the even narrower industrial organic sector dropped 3.2%.

The result was that not only did earnings drop for the period, but sales also declined. For the 28 chemical companies that had reported by press time, earnings dropped an average 13% in the third quarter from last year's third quarter to a total of $983 million. Sales, meanwhile, fell an average 4% to just under $20 million. The result was that profit

In spite of overall earnings drop, only nine chemical companies registered declines

	THIRD-QUARTER 1991						NINE-MONTHS 1991			
	Sales	Earnings[a]	Change from 1990		Profit margin[b]		Sales	Earnings[a]	Change from 1990	
	($ millions)		Sales	Earnings	1991	1990	($ millions)		Sales	Earnings
Air Products	$ 738.4	$ 58.4	−10%	2%	7.9%	7.0%	$ 2,206.5	$ 166.9	−2%	−3%
American Cyanamid	1,118.1	56.3	6	8	5.0	4.9	3,851.3	292.9	12	14
Arco Chemical	705.0	35.0	4	−38	5.0	8.2	2,090.0	120.0	1	−50
Betz Laboratories	170.3	19.9	11	13	11.7	11.5	500.0	57.0	13	15
Cabot	na	na	na	na	na	2.5	na	na	na	na
Crompton & Knowles	115.1	8.4	19	20	7.3	7.3	340.3	27.3	18	20
Dow Chemical	4,502.0	223.0	−8	−21	5.0	5.8	14,244.0	821.5	−3	−26
Ethyl	623.1	55.3	0	−2	8.9	9.0	1,915.1	158.3	4	−4
First Mississippi	139.5	5.3	3	23	3.8	3.2	423.0	7.7	6	20
H. B. Fuller	213.9	8.2	5	27	3.8	3.2	632.4	18.9	7	45
Georgia Gulf	206.4	15.6	−11	−33	7.5	10.0	656.0	49.3	−7	−35
B. F. Goodrich	649.5	20.7	2	−59	3.2	8.0	1,864.2	26.1	0	−74
W. R. Grace	1,621.6	49.6	−3	10	3.1	2.7	4,971.9	138.0	3	7
Great Lakes Chemical	320.5	39.2	20	11	12.2	13.2	985.7	117.8	27	13
Hercules	717.0	34.5	−12	17	4.8	3.6	2,219.0	101.7	−7	9
IMC Fertilizer	258.7	20.0	−3	−13	7.7	8.6	847.4	67.9	−1	7
Imcera	381.3	23.1	1	38	6.1	4.5	1,243.3	84.3	8	40
International Flavors	na	na	na	na	na	16.2	na	na	na	na
Loctite	140.3	19.3	1	10	13.7	12.7	419.7	58.4	2	14
Lubrizol	357.6	28.8	−2	−25	8.1	10.5	1,100.0	91.8	2	−9
Monsanto	2,042.0	116.0	−5	57	5.7	3.5	6,738.0	555.0	−1	15
Morton International	475.0	34.1	5	1	7.2	7.5	1,458.2	108.6	10	5
Nalco Chemical	345.8	34.7	18	6	10.0	11.2	985.0	100.4	14	5
Olin	551.3	15.2	−16	6	2.8	2.2	1,680.7	57.2	−14	−24
Petrolite	81.1	4.0	11	45	4.9	3.8	242.3	10.6	12	6
Quantum Chemical	573.0	−38.1	−8	def	def	def	1,895.7	−58.9	0	def
Rohm & Haas	672.1	39.5	−2	−14	5.9	6.7	2,104.7	133.6	−2	−21
Stepan	106.4	3.8	5	7	3.6	3.5	313.3	8.9	7	−23
Union Carbide	1,751.0	32.0	−10	−61	1.8	4.2	5,359.0	169.0	−7	−44
Witco	420.4	21.2	0	8	5.0	4.7	1,240.0	54.0	2	−6
TOTAL[c]	$19,995.4	$ 982.8	−4%	−13%	4.9%	5.4%	$62,526.6	$3554.7	0%	−14%

a After-tax earnings from continuing operations, excluding significant nonrecurring and extraordinary items. b After-tax earnings as a percentage of sales. c For 28 companies reporting.

margins for the 28 companies averaged 4.9%, down from 5.4% a year earlier.

Although the 13% decline may seem substantial, it still is less than the 18% drop recorded in the second quarter this year and it is a smaller annual decline than in any of the eight previous quarters, except for the first quarter of this year when earnings fell just 8% on a year-to-year basis.

However, on a quarter-to-quarter basis, these chemical companies showed up very badly in the third quarter. Although the third quarter is normally weak, this year's earnings fell 23% between the second and third quarters, and sales dropped 6%.

For the first nine months of this year, combined earnings for the 28 companies totaled $3.55 billion, down 14% from the same period last year. Combined sales for the period remained about the same as a year earlier, at $62.5 billion. The effect on profitability was to lower profit margins to 5.7% in the first nine months of 1991 from 6.6% in the same period a year earlier.

An indication of the effect of commodity chemicals on chemical company earnings is that of the 28 companies that had reported by press time, just nine reported earnings declines for the third quarter. Not included is Quantum, whose loss of $38.1 million in this year's third quarter makes last year's third quarter loss of $1.4 million look almost bearable. And Ethyl's earnings decrease amounted to just 2%. The remaining declines were in the double-digit range—but they were earnings nonetheless, not losses.

Most of these nine companies, and especially those with the largest

NINE-MONTHS 1991		12-MONTHS RUNNING DATA			
Profit margin[b]		Change from 1990		Profit margin[b]	
1991	1990	Sales	Earnings	1991	1990
7.6%	7.7%	1%	10%	8.1%	7.5%
7.6	7.5	9	18	7.0	6.5
5.7	11.6	6	−40	6.6	11.8
11.4	11.1	14	16	11.2	11.0
na	3.3	na	na	na	2.7
8.0	7.9	18	20	7.8	7.7
5.8	7.6	3	−29	5.6	8.1
8.3	9.0	4	−5	8.3	9.2
1.8	1.6	2	−20	1.2	1.5
3.0	2.2	7	38	3.2	2.5
7.5	10.8	−6	−49	7.7	14.3
1.4	5.5	0	−69	1.6	5.3
2.8	2.7	6	2	3.1	3.2
12.0	13.4	27	14	12.1	13.5
4.6	3.9	−4	93	4.2	2.1
8.0	7.4	0	8	8.3	7.6
6.8	5.2	11	52	6.4	4.7
na	17.2	na	na	na	16.3
13.9	12.4	14	16	12.3	12.1
8.3	9.4	8	6	8.4	8.6
8.2	7.1	2	−1	6.3	6.5
7.4	7.8	11	1	7.2	7.9
10.2	11.1	14	6	10.4	11.2
3.4	3.9	−9	−39	2.8	4.2
4.4	4.6	11	1	4.2	4.6
def	0.6	6	def	def	1.2
6.3	7.9	0	−11	6.1	6.9
2.8	3.9	8	−12	2.9	3.5
3.2	5.2	−8	−37	3.4	5.0
4.4	4.7	3	−4	3.9	4.2
5.7%	**6.6%**	**2%**	**−15%**	**5.5%**	**6.6%**

def = deficit. na = not available.

earnings declines, are involved heavily in commodity chemicals. Included are such companies as Dow Chemical with a 21% decline, Arco Chemical with a 38% decline, B. F. Goodrich down 59%, and Union Carbide down 61%.

These nine companies that reported declines are large enough that they accounted for about 44% of total chemical company earnings in the third quarter. However, in the third quarter of 1990, they accounted for 58% of total chemical company earnings, showing the magnitude of their decline.

If these nine companies plus Quantum are eliminated from the sample, however, instead of the 13% decline in earnings averaged for the 28 companies, the remaining 18 chemical companies posted an average 17% increase in earnings.

For Dow, the problem was apparent in its hydrocarbons and energy unit, which includes ethylene. In the third quarter, this segment of the company posted a 23% decline in sales to $442 million and a loss in operating income of $20 million. Carbide's net income for its chemicals and plastics unit fell 86% to $11 million in the quarter.

Earnings for oil companies with large chemical operations dropped 10% in the third quarter to a total of almost $2.64 billion on a 9% sales decline to $81.5 billion. Profit margins slipped slightly to 3.2% in the quarter from 3.3% in the comparable three-month period last year. For the nine months, oil company earnings were up 8% to $10.1 billion, and sales rose 1% to $251 billion. Profitability increased to 4.0% from 3.8% in the first nine months last year.

Oil companies also had their problems with petrochemicals. For Mobil, although total chemical sales were down 6% to $939 million for the quarter, sales of petrochemicals declined 13% to $451 million. This decrease offset a 1% gain in plastics sales and a 63% increase in sales of other chemical products. Chemical earnings at Mobil dropped 55% to $38 million for the quarter.

Texaco's earnings from chemical operations fell 75% in the quarter to just $3 million. Texaco says this is the eighth consecutive quarter that profit margins for commodity chemicals have been depressed because of oversupply conditions throughout the world.

Exxon, however, reported improvement in overall chemical earnings, but the improvement was all overseas. The company posted a 23% increase in chemical earnings to $85 million. However, in the U.S., chemical operations yielded a 23% drop to $65 million.

And Fina (formerly American Petrofina) reported chemical profits were down substantially when compared with last year's third quarter. Ron W. Haddock, the company's president and chief executive officer, said, "Styrene margins were 68% lower than in last year's third quarter due to industry's increased production capacity; lower demand, resulting at least in part from the economic recession; and higher raw material costs."

Diversified companies producing chemicals reported earnings that

Ground rules for C&EN earnings analysis

C&EN's quarterly report on financial performance of the U.S. chemical industry contains data from the 30 largest U.S. basic chemical companies and from 20 oil and diversified companies, each with more than $200 million in annual chemical sales, plus nine pharmaceutical companies.

To be included in the table of basic chemical producers, a company must have at least 50% of its sales in chemicals. That is why Du Pont, for example, is included in the table of diversified manufacturers.

In referring to chemical sales, C&EN means those chemicals whose molecular composition has been changed in the course of manufacture. Hence, chemical sales include those of traditional categories of basic petrochemicals and inorganics, organic intermediates and inorganic compounds, polymers such as plastics and fibers, and agricultural chemicals and specialty derivatives.

In listing earnings, the survey gives after-tax income for continuing operations before nonrecurring items and extraordinary charges. Foreign currency translations are included.

Drug companies continue to be only group showing earnings gains

	THIRD-QUARTER 1991						NINE-MONTHS 1991					
	Sales	Earnings[a]	Change from 1990		Profit margin[b]		Sales	Earnings[a]	Change from 1990		Profit margin[b]	
	($ millions)		Sales	Earnings	1991	1990	($ millions)		Sales	Earnings	1991	1990
OIL AND GAS COMPANIES												
Amoco	$ 7,011.0	$ 365.0	−11%	−4%	5.2%	4.8%	$ 21,091.0	$ 1,163.0	−6%	−7%	5.5%	5.6%
Chevron	10,000.0	231.0	−6	−28	2.3	3.0	30,600.0	1,076.0	6	22	3.5	4.8
Exxon	27,520.0	1115.0	−5	4	4.1	3.7	85,472.0	4,480.0	4	30	5.2	4.2
Fina	837.8	7.7	−21	−71	0.9	2.5	2,477.3	20.2	−11	−81	0.8	3.8
Kerr-McGee	832.2	26.8	−13	−38	3.2	4.5	2,402.0	66.8	−6	−33	2.8	3.9
Mobil	15,025.0	395.0	−8	47	2.6	1.6	46,054.0	1,506.0	2	34	3.3	2.5
Occidental Petroleum	2,330.0	148.0	−14	49	6.4	3.6	7,487.0	376.0	−7	41	5.0	3.3
Phillips Petroleum	2,970.0	56.0	−10	−69	1.9	5.4	9,405.0	275.0	1	−10	2.9	3.3
Sun Co.	2,950.0	0.0	−10	nm	nm	1.0	8,960.0	105.0	−2	−46	1.2	2.1
Texaco	9,356.0	286.0	−15	−25	3.1	3.5	28,567.0	970.0	−1	−9	3.4	3.7
Unocal	2,684.0	9.0	−13	−93	0.3	3.9	8,126.0	89.0	−4	−48	1.1	2.0
TOTAL	**$81,516.0**	**$2639.5**	**−9%**	**−10%**	**3.2%**	**3.3%**	**$250,641.3**	**$10,127.0**	**1%**	**8%**	**4.0%**	**3.8%**
DIVERSIFIED MANUFACTURERS												
Allied-Signal	$ 2,877.0	$ 80.0	−3%	−24%	2.8%	3.5%	$ 8,827.0	$ 227.0	−4%	−36%	2.6%	3.9%
Du Pont	9,426.0	504.0	−5	−5	5.3	5.4	28,930.0	1,643.0	0	−11	5.7	6.4
Eastman Kodak	4,926.0	317.0	3	−55	6.4	14.7	14,337.0	852.0	4	−34	5.9	9.3
Engelhard	571.6	21.2	−35	33	3.7	1.8	1,849.5	65.2	−19	33	3.5	2.1
FMC	967.5	41.7	3	18	4.3	3.8	2,891.5	142.9	5	11	4.9	4.7
3M	3,378.0	296.0	1	−12	8.8	10.1	10,116.0	895.0	4	−12	8.8	10.4
NL Industries	202.4	4.6	−8	−74	2.3	7.9	562.1	(17.2)	−5	def	def	14.0
PPG Industries	1,393.5	68.9	−5	−36	4.9	7.3	4,248.1	169.9	−6	−54	4.0	8.3
Vulcan Materials	289.2	30.2	−6	−28	10.5	13.7	752.7	53.9	−10	−46	7.2	12.0
TOTAL	**$24,031.3**	**$1363.7**	**−3%**	**−28%**	**5.7%**	**7.6%**	**$ 72,513.9**	**$ 4,031.7**	**0%**	**−23%**	**5.6%**	**7.2%**
PHARMACEUTICAL COMPANIES												
Abbott Laboratories	$ 1,653.7	$ 251.6	10%	14%	15.2%	14.7%	$ 4,990.3	$ 774.0	12%	13%	15.5%	15.4%
American Home Products	1,875.8	384.9	8	21	20.5	18.2	5,259.6	1,002.7	2	20	19.1	16.1
Baxter International[c]	2,212.0	156.0	10	16	7.1	6.7	6,531.0	407.0	10	def	6.2	def
Bristol-Myers Squibb	2,757.1	563.4	5	14	20.4	18.9	8,222.2	1,545.5	9	17	18.8	17.5
Eli Lilly	1,341.3	297.5	5	16	22.2	20.0	4,153.1	1,003.6	11	15	24.2	23.3
Merck	2,117.4	552.4	11	19	26.1	24.3	6,288.8	1,591.9	13	19	25.3	24.0
Schering-Plough	887.8	156.0	12	11	17.6	17.6	2,750.0	496.6	9	14	18.1	17.2
Upjohn	831.7	140.2	11	25	16.9	15.0	2,490.4	401.0	12	17	16.1	15.4
Warner Lambert	1,266.5	143.8	7	15	11.4	10.5	3,721.9	437.9	8	15	11.8	11.0
TOTAL	**$14,943.3**	**$2645.9**	**8%**	**17%**	**17.7%**	**16.4%**	**$ 44,407.4**	**$ 7,660.2**	**9%**	**26%**	**17.2%**	**14.9%**

a After-tax earnings from continuing operations, excluding nonrecurring and extraordinary items. b After-tax earnings as a percentage of sales. c Contains nonrecurring item in nine-months 1990. **def** = deficit. **nm** = not meaningful.

were down a much greater 28% in the quarter to $1.36 billion on a sales decline of 3% to $24.0 billion. Profit margins fell to an average 5.7% from 7.6% in third-quarter 1990. For the nine months, earnings were down 23% to $4.03 billion on flat sales of $72.5 billion. Again profit margins fell, this time to 5.6% in the first nine months from 7.2% in the same period last year.

As in the past couple of years, only pharmaceutical companies registered healthy results in the quarter, with earnings up 17% to $2.65 billion on an 8% sales gain to $14.9 billion. Profit margins for the group increased to 17.7% in the third quarter compared with 16.4% in the same period last year. In the first nine months, earnings rose 26% for this group to $7.66 billion on a 9% sales rise to $44.4 billion. The result on profit margins was an increase to 17.2% in the first three quarters this year from 14.9% in the same period in 1990. □

Paper industry changes shake supplier lineup

The pulp and paper industry in Canada—and across all of North America—is at what James Sigurdson calls "a fascinating crossroad." Market, environmental, and other pressures are forcing companies to change the way they operate both their pulp mills and their paper mills.

Traditionally a conservative industry, this simultaneous change has been traumatic for the mills, says Sigurdson, managing director of Law, Sigurdson & Associates, a consulting firm in Toronto. And, he adds, it will mean a new lineup of winners and losers among the companies that supply the mills with chemicals and industrial minerals.

Three major changes are rolling through pulping and bleaching. Kraft bleacheries are changing their bleaching chemicals to meet new environmental regulations. Increasing output of mechanical pulps is making its mark on pulp markets and bleaching chemicals. And the growth of recycled fiber is changing pulp markets.

In papermaking, changes have centered on printing and writing papers, where the move to alkaline papermaking has had a tremendous impact. Alkaline papermaking capacity will increase from 19% of total fine-paper capacity in 1985 to 50% in 1995. This trend already has raised filler levels.

Sigurdson told a recent industrial minerals conference in Toronto that sodium silicate is among the largest winners in the pulping and bleaching arena.

The rising use of mechanical pulping and, to a lesser extent, chemical pulping and papermaking, has given sodium silicate consumption in the mills a major boost. Sodium silicate also is being used in paper deinking and in recycling circuits, where it helps repulping and acts as a collector-processing aid. Sigurdson expects sodium silicate demand to triple, from 23,600 metric tons in 1987 to 68,500 metric tons by 1995. That, says Sigurdson, likely will open up more opportunities for glass-quality silica deposits.

Lime and limestone demand in the pulp and paper sector always has been substantial. And it will get even bigger, says Sigurdson, as mills change to greater chemical recycling. He says lime and limestone consumption in Canadian mills will jump 30% between 1987 and 1995 to 388,100 metric tons.

Soda ash, which is used as an alkali and a replacement for sodium hydroxide in pulping, is another potentially big winner as a result of changes in the pulp mills. Sigurdson says consumption of soda ash in kraft pulping and in paper recycling will grow from 18,000 metric tons in 1987 to 36,500 metric tons by 1995. That's better than a 9% average annual growth rate for a usually slow-growing material.

Increased capacity for kraft pulping is giving a boost to talc's prospects in Canadian pulp mills. Talc consumption in these mills is expected to increase almost 76% between 1987 and 1995 to 36,700 metric tons. The new kraft mills in British Columbia and Alberta are providing most of the thrust.

Paradoxically, sulfur is both a winner and a loser. It is a winner because sulfuric acid consumption in Canadian pulp mills likely will increase 62% or so to 392,400 metric tons in 1995. That will mean more elemental sulfur to make the sulfuric acid.

But, in Canadian kraft mills, the use of elemental sulfur itself is dropping dramatically. In part, mills are switching to sulfuric acid for their sulfur values. But they are also using sodium sulfate, which is a by-product from chlorine dioxide generators. In mills across Canada, demand for elemental sulfur will plummet from 211,000 metric tons in 1987 to a miserly 90,000 metric tons in 1995.

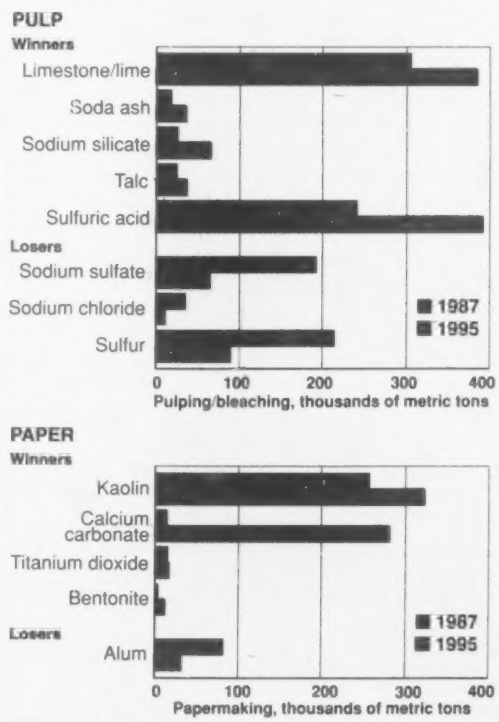
Elemental sulfur is not the only loser as a result of changes in Canadian pulping and bleaching. Sodium sulfate has gone from being a prized chemical for obtaining base sulfidity in kraft mills to being a "drug on the market," says Sigurdson. The reason: those chlorine dioxide generators and their sodium sulfate by-product.

Some kraft mills with large chlorine dioxide generators are putting as much as 5000 metric tons of material down the sewer each year, he points out. By recovering this material, demand for sodium sulfate is expected to drop to 66,400 metric tons in 1995. That's 66% lower than its 1987 level.

Generator chemicals also are hitting salt demand at the mills. Sodium chloride use will drop to 30% of 1987 levels, slumping to only 10,000 metric tons by 1995.

In the papermaking end of the pulp and paper industry, the big winner under alkaline conditions is calcium carbonate—both ground and precipitated. Generally, the precipitated material is used as sheet filler, whereas ground material is

Chemical demand in pulp and paper to change dramatically by mid-1990s



Source: Law, Sigurdson & Associates

used more as a coating pigment. In the Canadian market, both uses are booming, and Sigurdson expects to see demand rise from 12,100 metric tons in 1987 to a whopping 281,700 metric tons in 1995.

Many of the large fine-paper mills in Canada are putting calcium carbonate plants on site at the mill. There are now about 25 precipitated calcium carbonate plants being built or serving mills with "over the fence" filler supply in North America.

Another big winner is bentonite, a clay used as a filler in paper. As the mills move to alkaline papermaking and as filler levels rise, mills need more sophisticated retention and drainage systems. Although many of the products being used are polyacrylamides, some of these retention systems use bentonite in combination with them. As a result, Sigurdson expects bentonite demand to hit 11,800 metric tons in 1995, up from 2800 metric tons in 1987.

Kaolin is under pressure in the Canadian paper filler market. Demand for kaolin will continue to grow, but much more slowly than before. Demand in uncoated sheet mills will decline, as these mills move to alkaline processes and to carbonate fillers. But growth in coated groundwood paper in Canada will offset this decline and will push total kaolin demand up from 259,100 metric tons in 1987 to 320,300 metric tons by the middle of this decade.

Titanium dioxide also will hold its own in the Canadian paper market, despite the loss of some business to carbonate fillers. The call for whiter, brighter paper products will help keep titanium dioxide demand solid through 1995, if not much higher than it was in 1987.

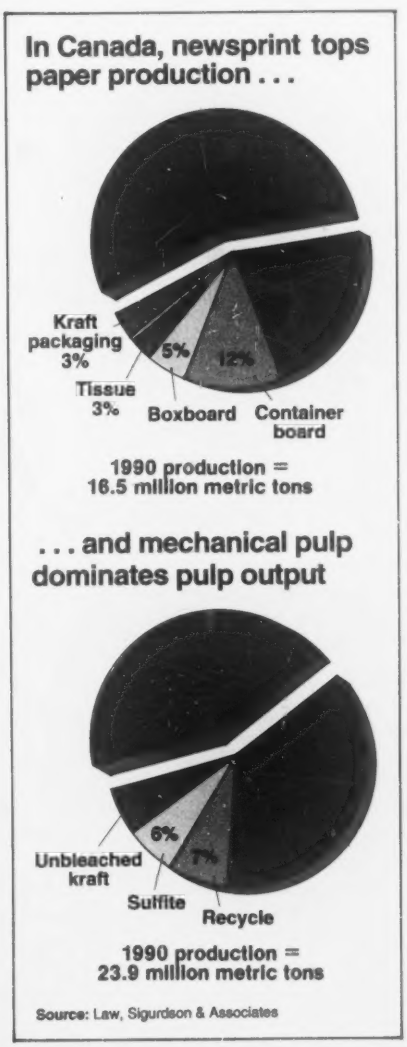
However, the use of alum, or aluminum sulfate, has dropped markedly at newsprint mills, and the switch to the alkaline process has hurt alum demand in fine papers. As a result, says Sigurdson, alum will be a big loser in Canadian paper mills. He estimates that demand will drop about 64% between 1987 and 1995 as a result of the process changes taking place in these mills.

Overall, Sigurdson thinks the Canadian pulp and paper industry will continue to provide a dynamic market for industrial minerals and other chemicals. Producers are expanding their paper product lines. And they are becoming much more sophisticated. This alone spells bigger markets for industrial minerals.

In addition, Sigurdson says the recession plaguing the pulp and paper industry will disappear. And the industry will overcome its problem of overcapacity, emerging stronger and with a high level of productivity.

Raw materials suppliers will find that the Canadian pulp and paper industry will be demanding more sophisticated products. Much of the industry is buying raw materials on a total "cost-in-use" basis, he says. And mill managers now are much more willing to switch products—and even processes—to meet market or environmental requirements.

Earl Anderson



Australian chemical industry battles image

Future development of industry in Australia is the subject of numerous studies and planning efforts by a variety of concerned groups. One prominent study has been conducted by a chemical industry task force for the state of New South Wales. Although restricted primarily to New South Wales, Australia's most populous region, reports from the task force are probably more generally applicable and provide a reasonable outlook for the Australian chemical industry in the near future.

The task force stemmed from a previous investigation commissioned by the New South Wales government that identified a number of industrial and commercial targets for development. Prominent among them was the chemical industry. The task force included industry, government, business, and labor inputs and was chaired by Bruce J. McAllen, head of ICI Australian Operations.

A frequently expounded view is that the chemical industry in Australia is "under siege and faltering." A task force report explicitly notes that the activities of environmental extremists have been concentrated on the chemical industry, probably because it is the most accessible target. To some, the operation of chemical plants is considered antisocial, and there are even advocates for eliminating chemical plants altogether. As a result, some pessimistic observers foresee future deindustrialization.

These are the images that have been created in the popular press in Australia. The facts, however, are quite different from the images, says the task force.

The Australian chemical industry is highly regulated, and most companies are in compliance with regulatory directives. Those that aren't in compliance have been fined or otherwise penalized. The industry is essential to the economic health of New South Wales because of its large payroll and the tax revenues it generates. The products from the industry are essential to the well being of the society and include products for medicine, transportation, materials, and agriculture.

NSF's Chemistry Division Looks for Creative Solutions to Budget Woes

Faced with yet another disappointing funding increase, resourceful division shifts monies among programs to stretch grant support

Pamela S. Zurer, C&EN Washington

The chemistry division of the National Science Foundation is physically situated, like the rest of the agency, in a slightly dilapidated office building in downtown Washington, D.C. But given the pressures on the division, its situation might more aptly be described as between a rock and a hard place.

The division is the source of about one fifth of all federal support for academic research in chemistry, directing about 80% of its resources to individual scientists. Yet its budget hasn't increased in real dollars in years. It turns down many more worthwhile grant proposals than it funds. And many of the applicants who do succeed in winning NSF grants complain they are too small.

"Probably 80% of the proposals we get are worthy of support," says division director Kenneth G. Hancock. "Instead we support only one in three. We support that one at probably only two thirds of what it asks for. And what it asks for is probably artificially trimmed in recognition of reality."

At the same time that the pressure for its limited dollars has been increasing, the division has been stretching to take on more and more responsibility for educating future generations of chemists by vigorously supporting programs for undergraduates and postdoctoral fellows.

"We've taken the position it's appropriate for the chemistry division to be more than just a research division," Hancock says. "We should be a disciplinary division that is focused on coupling research and education."

Up to a month ago, it looked like this year there might be some relief from the pressure. The division was expecting its fiscal 1992 budget to grow to about $112 million, up 10% from the year before. After having to make do since 1987 with small increases that didn't even keep up with inflation, the division's officers knew exactly where they wanted to put the extra money.

"We need an across-the-board increase in the purchasing power of grants," says Hancock. "The American Chemical Society did an analysis that found the average NSF chemistry grant has lost 22% of its purchasing power in the past four to five years."

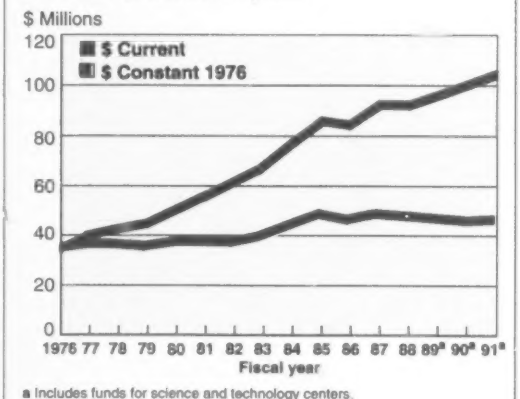
Also, the division wanted to add $3.1 million to fund its share of projects in materials synthesis and processing, a new multidisciplinary initiative. Another $900,000 was to go to programs aimed at women, minorities, and undergraduates.

Last month, however, the hoped-for 10% increase evaporated. When Congress finally completed work on NSF's 1992 budget—well after the Oct. 1 start of the fiscal year—it had given the agency less than it requested for research. Although NSF is still working out exactly how to divide the smaller pie, it now appears likely the chemistry division will get only about a 7% increase to $109 million.

By the time the division's advisory committee met on Oct. 31, Hancock and his coworkers had devised a strategy to cope with the disappointment. By encouraging chemists to take advantage of a new NSF-wide Academic Research Instrumentation (ARI) program, Hancock explained, the division could shift funds out of its own program for shared instruments, where demand of late has been low. That would allow it to put all of its funding increase into the physical, organic, inorganic, and analytical chemistry programs and still have the money for materials initiative and educational programs.

That sort of flexibility in the face of severe constraints has won the division the respect of the chemical community. "One of the things I've been proudest of as a chemist is the inventiveness of this division in trying to devise productive ways to serve science," said advisory committee chairman Larry R. Faulkner, dean of the University of Illinois' College of Liberal Arts & Sciences.

Chemistry division budget has seen no real growth in years



a Includes funds for science and technology centers.
Source: National Science Foundation

At its meeting, the committee voted to back the division's plan for 1992. "The strategy responds to the most pressing problem of the chemical community," Faulkner said. "Institutions are having trouble with matching funds so they are not applying for new instruments now. Eventually the need for instrumentation will resurface. But for 1992 the most pressing problem is the lagging purchasing power of grants."

A few years ago, the advisory committee was more concerned about the number of grants the chemistry division was making than their size. "They told us: 'You are already declining so many high-quality proposals we don't know how you can turn down any more,'" Hancock says.

Therefore, over the past few years the division has maintained the number of grants it supports at about 900 each year. That has meant the average grant size remained for several years in the mid-$80,000s, a figure that includes indirect costs.

"NSF grants are in fact grants-in-aid," Hancock says. "It's never been pretended that they pick up the full costs of a research project. We would if we could. We are trying to make the resources stretch to include as many people and high-quality projects as we can without creating a fleet of three-wheeled buses."

But the situation has deteriorated of late, suggesting some research vehicles are stuck on the highway missing a wheel. The advisory committee now is recommending the division concentrate on beefing up grants. That could mean turning down even more borderline applications—a task chemistry division staff already anguish about.

"The most difficult thing, when you are working to encourage people, is to decline proposals that are worthwhile because of insufficient funds," says Henry N. Blount III, an analytical and surface chemistry program officer.

"We're aware of how much of a toll inflation has taken in research," says Margaret A. Cavanaugh, a program officer in inorganic chemistry. "In each program people are wrestling with grant size as opposed to the number of awardees. What should you do? Make room for new people or increase grant size?"

"The hardest part is saying no," says George M. Rubottom, a program officer in organic synthesis. "We say it an awful lot. We try to turn it into a mentoring session to help people do better in the next round."

But sometimes, Hancock points out, there's really no advice to give. "There is nothing wrong with the large majority of proposals. If we had three times as much money we would be delighted to support them."

The division's budget for individual research grants is divided among four disciplinary divisions: organic, inorganic, physical, and analytical and surface chemistry. (Organic is further subdivided into organic synthesis and organic dynamics.) In fiscal 1991, physical chemistry was initially allotted about 30% of the funds, organic about 25%, inorganic about 17%, and analytical/surface chemistry about 13%. The allocation is based on past experience and expectations of future needs.

"The basic principle we try to use is the concept of equal quality," Hancock says. "The projects we fund should be of comparable quality in all of the subfields of chemistry. We don't want to fund mediocre chemistry X and be declining excellent science Y. To a very large degree the incoming proposals, in number and quality, determine where the resources go."

In addition, Hancock withholds a portion of the available money as a reserve. It is distributed later in the year as the pressures on the programs become better known. Some programs get more of the reserve, some none.

The chemistry division has no set deadlines for grant proposals, accepting them anytime during the year. Once received at NSF, staffers decide to which program proposals should be assigned, so that like compete with like. "Most of the time it's fairly clear where a proposal should go," Cavanaugh says. "But chemistry is becoming interdisciplinary. Inorganic, for example has borders with biochemistry and biophysics and materials research in addition to interfaces with inorganic and organic and analytical chemistry."

If a proposal straddles more than one NSF division—say, chemistry and molecular biosciences—it may be reviewed by reviewers from both communities. If successful, it may be jointly funded by both divisions.

After a home has been found for each proposal, the program officer decides who will review it. In the chemistry division, the staff looks for six reviewers who are asked to mail or fax in their evaluation within a month. Before a funding decision is made, the application must have at least three substantive reviews and virtually always has at least four.

"That's the heart of our job," Cavanaugh says. "No matter whether the proposal is successful or not, if we provide the person who wrote it with the best possible evaluation

C&EN staff photos

Cavanaugh, Hancock, Blount, and Rubottom (clockwise from above) regret high-quality proposals that don't get funded, the hard funding choices, the difficulty of saying no

and feedback that's a real service to the community."

Reviewers and staff judge proposals using four criteria: the proposal's scientific merit; the capability of the principal investigator to do the work; the utility or relevance of the research; and its effect on the scientific infrastructure, such as education and human resources.

"We are deciding among very many excellent proposals," Hancock says. "We think we're better off getting as much input from reviewers as we can. We invite them to comment on everything and then it's up to the program officers to sort out the wheat from the chaff."

Some scientists are uneasy about NSF's recent focus on what it terms infrastructure. They worry that scientific merit is in danger of taking a back seat to other concerns. Hancock says the agency has defined the term very broadly and set itself wide goals.

"Infrastructure includes worrying about the undue concentration of resources in one individual or one institution or one region of the country," he says. "But it also encompasses such issues as the participation of women and minorities and of undergraduate schools as well as doctoral institutions.

"To me it seems it also addresses such issues as scientific talent," he continues. "Do we concentrate on what may be faddish today and ignore something that has potential for tomorrow? Do we worry about paying attention to experiments which are high risk or proposals which challenge established thought and could be very controversial?

"All of those are infrastructure questions. We're saying, 'Don't just take the easy way out and only worry about scientific merit.' But other concerns are never a substitute for scientific merit. We never fund a mediocre proposal just because it's relevant or because it happens to be the only proposal from that state this year."

Once peer reviews are in, the program officers decide which grants get funded and at what level. In chemistry, the program officers normally work in pairs consisting of one permanent staff member and one visiting scientist (rotator) on one-year leave from his or her university.

(About half of the chemistry division staff are visiting scientists. "It brings in people who are absolutely up-to-date in their field and complements the expertise of permanent staff," Hancock says. "And the rotators go back to their universities with first-hand knowledge of how the system works.")

The program officers' recommendation is then reviewed by both deputy director John B. Hunt and Hancock. "In the very large majority of cases there is excellent concurrence on the yes/no decision," Hancock says. "There is some discussion on a small fraction of cases about the level of support. That comes about because we try to keep a balance among the different subfields."

The chemistry division's biggest effort in education is in the NSF-wide Research Experiences for Undergraduates (REU) program. Set up in 1987, its goal is to give undergraduates a taste for research by having them spend the summer working in a lab. The REU program is modeled after the old NSF Undergraduate Research Program (URP), in which many of today's chemists took part during the 1960s and 1970s.

"We really have been leaders in this [REU] program," Hancock says. "That program has grown to $3 million for us over four years when the total growth for the chemistry division has only been about $8 million." The chemistry division is now supporting 57 REU sites that are serving about 600 students a year—a quarter of the total supported by NSF as a whole. Almost half of the participants are women and 15% are underrepresented minorities.

"Chemists think that REU is so important that our advisory committee was willing to sacrifice research grant funding to make it a going concern," Hancock says. "Chemistry is a hands-on science. Chemists learn by doing."

Joseph Reed Jr., the division's coordinator for the REU program, says proposals for participation in REU are intensively screened by a review panel. "The environment is critical. We want the students to feel they are part of the community. Do the faculty want to give students a real research experience? Just relegating them to graduate students or postdocs is not what we want. We are looking for faculty involvement."

The chemistry division also devotes about $1.5 million per year to postdoctoral fellowships in chemistry—a program that is not NSF-wide but originated within the division. New Ph.D.s are supported for one or two years of postdoctoral research and can apply for a leveraged starter grant if they go on to a tenure-track faculty position.

"The program encourages new Ph.D.s to broaden their experience and training," says special projects program officer Seymour J. Lapporte. "Beyond that it encourages

Lapporte (left) and Reed: chemists are sacrificing to make undergraduate research program a going concern

them to go into academic research and teaching."

Applicants for the fellowship must prepare original proposals focusing on the research they hope to pursue after their postdoctoral stint. The program has received between 110 and 160 applications each year and awards between 15 and 20 fellowships—a success rate of about 15%.

This year Lapporte will be managing the chemistry division's share of the new Materials Synthesis and Processing (MSP) initiative. The $25 million program, in which nine NSF divisions will participate, is aimed at encouraging interdisciplinary research on new and existing materials. In this first year, NSF is placing highest priority on electronic and photonic and biomolecular materials, but will also consider proposals addressing structural, magnetic, and superconducting materials.

The new initiative is a successor to the old materials chemistry and chemical processing program, a joint effort of the chemistry, materials science, and chemical and thermal systems divisions that began in 1987. Although the old program was only open to collaborative proposals, the new MSP initiative will also accept proposals from single investigators.

The chemistry division had expected to fund MSP proposals with part of its 1992 budget increase. Now that the increase has turned out to be smaller than expected, Hancock likely will move $3 million out of the divisions' Chemistry Instrumentation Program (CIP).

Last year the division spent about 16% of its budget on research instrumentation. About $10 million came out of the disciplinary programs' budgets to fund dedicated special-purpose instrumentation under individual research grants. Another $5 million or so came from CIP, which is directed by Reed. That program supports large shared instrumentation such as departmental mass spectrometers or computers. The grants pay for two thirds of the cost of the hardware and the university must come up with the rest.

However, the CIP program had been budgeted at $8.1 million for fiscal 1991. The $3 million it didn't spend was kicked back to the disciplinary programs. CIP simply didn't receive enough worthwhile proposals to justify using all its allocated funds, Reed says. "Why spend money on poor proposals?"

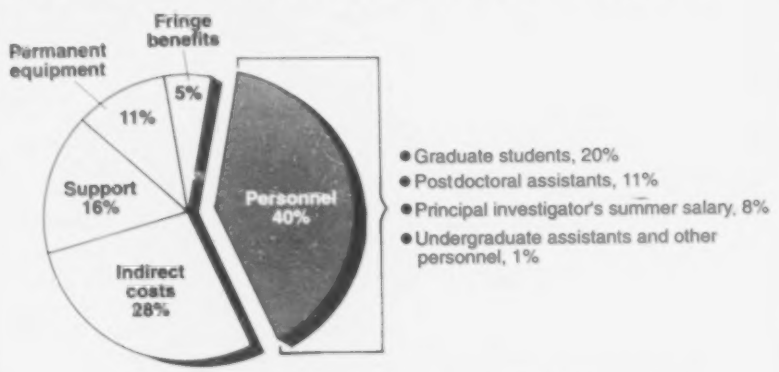
Hancock expects the proposal pressure on CIP to remain depressed for a while, perhaps because research institutions are having such a hard time coming up with the required matching funds. So he now plans to cut CIP's fiscal 1992 allocation to the $5 million level actually spent in 1991 to put the extra into research. The division also will encourage chemists to apply for shared instrumentation through the new NSF ARI program, which will provide half of the funds for instruments costing between $200,000 and $4 million.

That sort of continual juggling to stretch limited resources is typical of the division's staff and reflects their dedication to the chemistry community.

"The role of the program director is to try to support people in their research," Rubottom says. "That's the fun part of the job—the sense of being part of the research enterprise. It's like having a box seat at the World Series."

"When we talk about our responsibilities we're talking about people's livelihood," Hancock says. "If you submit a paper to *JACS* and you don't get it published, there are hundreds of other chemistry journals you can submit it to. But if you don't get a research grant from somewhere, it's hard to stay in business. What we do is life and death. We take it very seriously." □

Salaries take biggest chunk of average chemistry grant



Average 1991 chemistry research grant = $94,000 per year

Source: National Science Foundation

Air Pollution and Forest Damage

Regional air pollution is one of the man-made stresses causing gradual and subtle changes over wide, forested areas of the U.S. and Canada

William H. Smith, Yale University

The 1980s will be long remembered as a decade of intense and widespread concern for the vitality and integrity of forest ecosystems. Daily reports of deforestation in the tropics and forest decline in temperate latitudes greatly heightened social consciousness about forest health. As we enter the 1990s, a number of events relative to the interaction of air pollution with forests are occurring rapidly and continuing to heighten the consciousness of society toward forest ecosystems.

Part of what has helped to increase this concern is the 10 years of activity of the National Acid Precipitation Assessment Program (NAPAP). Created by Congress under the Acid Precipitation Act of 1980, NAPAP is mandated to perform a 10-year, multiagency, scientific, technological, and economic study to examine the relationships among energy production, acids and other pollutants resulting from emissions, and the effects of these pollutants on the environment (including forests), the economy, and human health. In 1990, the program issued three detailed "State of Science and Technology" reports that deal specifically with the effects of air pollution on vegetation and forests. This year, it published a summary document on all 27 state-of-science reports it has issued. An integrated assessment of air pollution risks is expected by the end of the year.

In November 1990, joint efforts of Congress and the executive branch culminated in major revisions to the federal Clean Air Act. These revisions, the first in 13 years, have important implications for ecosystem, as well as human, health. Last March, President Bush and Prime Minister Brian Mulroney of Canada signed an environmental accord specifically directed to reduce transboundary acid deposition. And during the past year and a half, the extraordinary changes in the governance of Eastern Europe have made people more aware of the devastating impact that industry and energy generation can have on natural environments, and especially the forests, there.

Almost half of Canada (45%) and one third of the U.S.—about 750 million hectares (or about 1.9 billion acres) altogether—is covered by forests. These forests grow in a full range of conditions from tropical to boreal and contain a large variety of coniferous and deciduous species.

Forests provide many ecological, economic, and cultural benefits to both countries. Besides the obvious forest products—such as lumber, wood fiber, water, and wildlife—they supply less obvious benefits, which include recreation, biological and landscape diversity, shade, wind reduction, sound attenuation, visual attractiveness and screening, water quality, flood and erosion management, soil and nutrient conservation, and storage and detoxification of persistent pollutants.

In addition, U.S. and Canadian forests are sinks for large amounts of carbon dioxide. Nearly all of the U.S. and Canada are in the temperate zone, where forests add 5 to 20 metric tons to their biomass per hectare per

year, which is equivalent to about 2.5 to 10 tons of carbon. Temperate forests rank third behind only tidal zones and rain forests in the amount of carbon they can store in a given year. Therefore, they play an important role in controlling the amount of carbon dioxide in the atmosphere and thus influence global warming.

In the U.S., forests range from pure stands of Douglas fir in the Pacific Northwest, to ponderosa pine in the semiarid West, to mixtures of oaks and southern pine in the South, to the complex multispecies hardwood forests of the Northeast. In Canada, a mixture of coniferous and deciduous species grows in the East, and conifers dominate the West. The softwoods in Canada consist largely of spruce, pine, and fir, whereas hardwoods are primarily poplar, birch, and maple. The forests of these countries receive different amounts of human attention ranging from no management to intensive management, depending, in part, on the products or services people expect from the forests.

Some observers believe the adverse effects of air pollution are important only when they can be measured in economic terms. This leads these observers to conclude that pollution should not be mitigated unless the costs of control are offset by equal or greater benefits. David T. Tingey and colleagues at the Environmental Protection Agency's Environmental Research Laboratory, Corvallis, Ore., argue, however, that "adverse effects" must be broadly viewed when assessing air pollutant stress on ecological systems. I fully agree that all forest products and services, whether or not they have been quantified in economic terms, are important when considering the adverse effects of air pollution.

Fundamentals of forest health

Understanding fundamental principles of forest health is essential for developing an accurate perspective on how regional air pollutants affect complex forest systems. Factors capable of causing injury, disease, and mortality in forests are termed stresses. These may be biotic (living) or abiotic (nonliving), natural or unnatural. Factors recognized to have widespread importance include climatic, pathologic, entomologic, and anthropogenic elements, as well as wildlife, fires, tree age, and competition among trees. Because trees are generally large and long-lived, their health integrates the influences of all stresses that have acted on them. Although the list of forest health problems is very long, disease and premature mortality in most forests remain the exception rather than the rule.

Forests in temperate zones have relatively low biological diversity and are relatively stable. Tree mortality is high in seedlings and early development stages, but medium to low in mature and old trees. Louise M. Tritton of the Department of Agriculture's Forest Service in Burlington, Vt., and Thomas G. Siccama of the School of Forestry & Environmental Studies at Yale University recently provided one of the few regional inventories of the proportion of standing dead trees in northeastern U.S. forests. They documented—over a wide diversity of forest histories, ages, species, and sites—that 5 to 36% of the standing trees are dead.

The significance of various stress factors in temperate zone forests varies greatly with tree age, soil type, aspect, elevation, and climate. For example, white-pine blister rust, which thrives better in cool temperatures, is an important disease in northern Wisconsin and northern New England, but less significant in southern Wisconsin and southern New England.

Management objectives also define the relative importance of specific stress factors. Unlike agriculture, where almost any stress causing a loss in productivity is important, the significance of a particular stress in a forest depends on the goals of the manager. Complete or partial defoliation of hardwoods during a single year caused by foliar pathogens or insects, for example, could cause significant economic loss in a forest being managed as a family campground, whereas a single year of defoliation in this same forest, if it was being managed for wood production or as a wilderness area, would be largely unimportant.

Temperate forest ecosystems, like all other ecosystems, are dynamic and, over time, are characterized by variability. Plant and animal diversity and forest productivity change with the developmental stage of such forests. Both biotic and abiotic stresses play fundamental and natural roles in the regulation of species composition and productivity.

In natural forests, perturbations caused by nonliving and living stress factors may be necessary to maintain maximum diversity and productivity. In temperate latitudes, many forest ecosystems have a natural tendency toward periodic perturbations at intervals of 50 to 200 years. These cycles cause waves of biological diversity and corresponding waves of production of living material. Insect outbreaks, fires, and windstorms—even when they cause massive destruction in the short term—may play beneficial and essential roles in the long term. They regulate tree species competition, succession, productivity, and nutrient cycling. In a sense, a forest at any given time is the result of a life-and-death competition among species, and the stresses that have acted on the forest are partly responsible for shifting and maintaining the balance of competition among species.

In a forest, ambiguous tree disease or decline—that is, decline or disease of uncertain cause—is the rule not the exception. Unambiguous stresses with catastrophic impact do occur, such as the 1938 hurricane in New England, the eruption of Mount St. Helens in 1980, and the 1988 wildland fires in Wyoming and California. Equally unambiguous are wide-area defoliations by tussock moths, eastern and western spruce budworms, and gypsy moths, and wide-area mortality caused by diseases, such as chestnut blight, Dutch elm disease, fusiform rust, and white-pine blister rust.

Although these stresses are dramatic, they are not the norm in forest dynamics. More typically, tree disease, decline, and death result from complex interactions of multiple stresses—and the relative importance of specific stresses is difficult to assess. The impacts of air pollution on forests fall into this ambiguous category.

A special and very important type of ambiguous tree disease is termed dieback/decline. It occurs when a large proportion of the trees of a particular species over an area of many square kilometers show symptoms of stress, unusual and consistent growth decreases, or die. Symptoms include chlorosis (a yellowing or paling of foliage), crown thinning, and dieback. Forest dieback/decline diseases are irregular in distribution and discontinuous, but recurrent, in time.

Dieback/decline is more characteristic of mature forests and generally results from sequential and complex interactions of multiple stress factors. Common nonliving stresses include drought and abnormally low and high temperatures. Living agents of particular importance include defoliating insects, borers and bark beetles, root-infecting fungi, and canker-inducing fungi. Typically, an abiotic stress initiates decline and a biotic one ultimately causes mortality. The nonliving stress is often a climatic one, such as less than normal precipitation.

In the U.S., dieback/decline is now especially important to sugar maple and American beech in portions of the northern hardwood forest (extending north from mid-Pennsylvania). In Quebec, many sugar maple stands are in decline, especially in the region south of the St. Lawrence River. From 1930 to 1960, very widespread decline and mortality of yellow birch occurred throughout New England, New York, and southeastern Canada. An important decline of white ash that was most severe in the Northeast during the 1950s may again be increasing.

The most widespread and serious declines over the past several decades in the U.S.'s central hardwood forest (from mid-Pennsylvania south through Virginia and Kentucky) have been associated with scarlet, pin, red, and black oak. The present distribution of oak decline is highly variable, but mortality reaches 20 to 50% in hard hit areas and has been especially severe in the George Washington and Jefferson national forests in Virginia. There is evidence that similar declines occurred earlier in this century in the southern Appalachians. And during this century, wide-area dieback/decline episodes of lesser importance in dogwood, sweetgum, yellow poplar, and magnolia have taken place in the central and southern hardwood forests (south of Virginia and Kentucky).

Conifers have also experienced dieback/declines over wide areas. Important North American exam-

Almost a third of U.S. forest acreage is managed intensively

Type	Description	Total size (thousands of hectares)	Management intensity
Unmanaged natural forest	Areas of low tree density and/or slow growth	120,000	None
Managed natural forest	Commerical forest land, recreation, and wilderness areas	190,000	Medium
Suburban forest	Specimen, shade, ornamental trees	80,000	High
Urban forest	Park, street trees	40,000	High
Plantation forest	Row pattern planting with regular spacing	20,000	High
Christmas tree plantation	Short rotation, holiday market	200	High
Forest tree seed orchard	Seed production areas	4	Very high
Forest tree nursery	Seedling production areas	6	Very high
Arboretums	Trees established for study, enjoyment	4	Very high

Stress factors cause disease and injury to forest trees

BIOTIC FACTORS

Primary causes of disease[a]		Primary causes of injury[b]	
Fungi	Nematodes	Insects	Mammals
Bacteria	Mycoplasma	Mites	Birds
Viruses	Insects	Rodents	Humans
Mistletoes	Mites		

ABIOTIC FACTORS

Primary causes of disease[a]	Primary causes of injury[b]	
Air pollution	Wind	Landslides
Drought	Fire	Avalanches
Salt	Temperature extremes	Harvesting
Adverse soil chemistry or physical structure	Moisture extremes	Pesticides
Nutrient deficiencies or excesses	Lightning	Ice, snow
Competition	Volcanic eruptions	Salt, other chemicals
		Radiation

a Disease is defined as abnormal physiology from chronic interaction with stress.
b Injury is defined as abnormal physiology from acute interaction with stress.

ples of the past 50 years include Alaska cedar, western white pine, and white spruce in the West; and shortleaf pine, other southern pines, and high-elevation red spruce in the East. These red spruce are currently in decline in some areas.

During the past decade, many forest species in Central Europe have also shown symptoms of decline. In some regions, the impact has been especially dramatic on silver fir, Norway spruce, Scotch pine, European beech, and various oak species. In Germany, the third national survey of forest health, conducted in 1985, found that in 55% of the forested area of the former West Germany, trees showed symptoms of stress on their foliage. The inventory recorded 33% of the symptomatic forests had low damage, 19% medium damage, and 3% heavy damage to tree leaves and needles.

Does air quality affect these declines? Unfortunately, scientific understanding of the interactive and sequential nature of stresses that cause forest decline is far from complete. The literature related to North American and European decline phenomena of the past century reveals as much speculation as evidence about causes, in part because no formally accepted rules of proof for decline diseases exist. Incidents of decline with the most conclusively documented causes have occurred in specific stands or very restricted regions.

The study of dieback/decline phenomena in forests in some ways resembles the study of cancer in humans. Cancer is recognized as a multistage process, and many cancers involve the interactions of multiple stresses. Assessing the specific factors involved in certain cancers and their relative importance with confidence is not possible because of the limits of current toxicology. Likewise, assessing the specific factors involved in wide-area forest decline exceeds the current limited capabilities of forest science.

Air pollutants and forest health

Regional air pollutants of greatest documented or potential adverse influence for forests include trace metals (most importantly heavy metals, such as cadmium, copper, lead, chromium, mercury, nickel, and zinc); acidic deposition (primarily the wet and dry deposition of sulfuric and nitric acids); and oxidants, especially ozone.

The response of trees to air pollution can be measured at both the plant and ecosystem levels. The various tissues and organisms of a specific forest ecosystem have very different thresholds for damage from air pollutants. When exposed to low levels of air pollution, the vegetation and soil function solely as sinks or receptors. At intermediate levels, individual plants or particular species may be subtly harmed through nutrient stress, impaired metabolism, predisposition to insect or microbial damage, or direct induction of disease. Exposure to high levels of air pollutants may induce acute disease or mortality of specific plants.

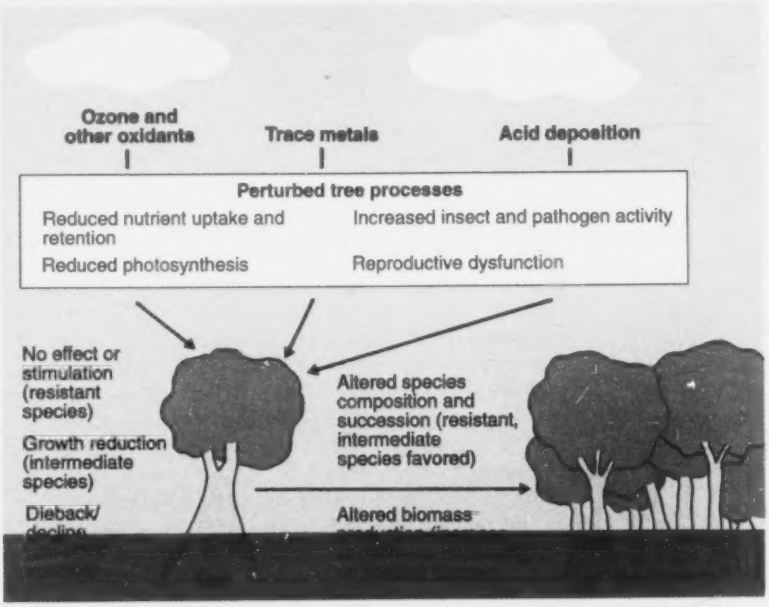
The impact of these interactions on a forest ecosystem is highly variable. When air pollution levels are low, the pollutant is transferred from the atmosphere to various plants and animals and to the soil. The impact on the ecosystem of this transfer could be undetectable and, therefore, innocuous; or it could be stimulatory—for instance, the pollutant could fertilize some of the plants. If an intermediate exposure to the pollutant is harmful to some component of the forest ecosystem, a subtle adverse response may occur, such as reduced productivity or biomass, alterations in species composition or community structure, or increased morbidity. With high exposure, ecosystem impacts may include gross reduction in the number of species, impaired energy flow through the ecosystem, reduced biogeochemical cycling of nutrients, changes in hydrology and erosion, climate alteration, and major impacts on other ecosystems that are affected by the forest.

Heavy metals

Human activities introduce heavy metals into the atmosphere primarily in particulate form. During high-temperature combustion in electric power stations, incinerators, steel mills, and motor vehicles, for example, metal elements and their oxides become volatilized. The elements of high volatility—such as cadmium, chromium, nickel, lead, thallium, and zinc—concentrate on the surfaces of fine airborne particles as they condense. Small particles with diameters of 1 μm or less are efficient collectors of heavy metals because of their large surface-to-volume ratios.

Preferential association of heavy metals with small particles is significant not only because these particles may escape emissions control, but also because they have long atmospheric residence times and, therefore, can be carried long distances. Depending on climatic conditions and topography, fine particles may remain airborne for days or weeks and be transported 60 to 600 or more miles from their source. Ecosystems downwind

Trees, forest ecosystems respond in complex ways to stresses from regional air pollution



Ozone and other oxidants, trace metals, and acid deposition from the atmosphere may affect trees and forests in a variety of ways. In sensitive species, certain pollutants may reduce nutrient uptake and retention, reduce photosynthesis, cause reproductive dysfunction, and increase the activity of insects and pathogens that harm trees.

The net result is that resistant species of trees may not be affected at all or may actually be stimulated because the trees they compete with have been harmed by the pollutants. Intermediate tree species, those that are somewhat sensitive to the pollutants, may experience growth reductions, but may show no other obvious effects, and sensitive tree species may show decline and dieback.

At the ecosystem level, the pollutants may cause altered species composition and succession because the resistant and intermediate tree species may be favored, while the sensitive species decline and die. Also, the pollutants may alter the net production of biomass. If the species that are favored by the air pollution usually tend to grow faster than the sensitive species, biomass production could actually be enhanced. If, on the other hand, the favored species grow relatively slowly, biomass production may be decreased

from major power-generating, industrial, or urban complexes receive both wet and dry atmospheric deposition that contains accumulated metals from multiple sources. Most fine particles and elements such as cadmium and lead are removed from the atmosphere with rain, snow, and fog, whereas most large particles and elements such as iron and manganese are deposited between precipitation events.

Extensive evidence indicates that heavy metals deposited from the atmosphere to forests accumulate either in the forest floor (the richly organic layer on top) or in the upper soil horizons (the uppermost soil layers under the forest floor). Because this accumulation is commonly in the part of the soil where the activity of roots and soil organisms is greatest, it has the potential to be toxic to roots and soil organisms and to interfere with nutrient cycling.

All the heavy metals, regardless of whether they are biologically essential, can be directly toxic to trees at some high levels of exposure. Only a few, however, have been documented to cause direct plant toxicity in actual field situations. Toxicity from copper, nickel, and zinc has occurred frequently, whereas toxicity from cadmium, cobalt, and lead has been seen only under unusual conditions. Even at high doses, chromium, silver, and tin have not been toxic in field situations. Trees have shown direct and acute heavy-metal toxicities only in the immediate vicinity of point sources.

In contrast, the lower exposures from heavy metals associated with regional deposition have the potential to interfere with nutrient-cycling processes over the long term. The high productivity of forest ecosystems is achieved and maintained through efficient nutrient cycling. For most forests, the elements required to maintain productivity cannot be sustained from annual precipitation and mineral substrates alone. The release of nutrients from the decomposition of organic material is also required.

Many hypotheses attempt to explain how heavy metals in regional deposition interact with nutrient cycling. Some of the most important are:

- Heavy-metal contamination of soil may interfere with the ability of soil biota to decompose organic matter in the forest floor. Heavy metals may bind with colloidal organic matter in the soil and increase its resistance to decomposition or directly harm or kill microorganisms or arthropods that are important for decomposition.
- A large number of soil enzymes—including free extracellular enzymes and enzymes bound to inert soil components, as well as active enzymes within dead cells and others associated with abiotic cell fragments—participate in important extracellular forest soil processes. By complexing the substrate, by combining with the active group of the enzyme, or by reacting with the enzyme-substrate complex, heavy-metal ions inhibit the reactions of at least 10 of these enzymes.
- Heavy metals may also reduce microbial processes in forest soils. Many studies of large metal-emitting point sources have shown that cadmium, copper, mer-

cury, nickel, lead, and zinc reduce the rates of microbial metabolism in soil. And under experimental conditions, cadmium, chromium, iron, lead, mercury, nickel, silver, and tin reduce nitrification, an important microbial process in both forest and agricultural soils.

• Forests frequently flourish in regions where the supply of soil nutrients is low, marginal, or poor. Forest ecosystems have evolved ways of conserving nutrients and maintaining tight control over nutrient cycling. In addition, trees have evolved critically significant symbiotic relationships with soil fungi and bacteria that enhance nutrient supply and uptake. Many heavy metals—including cadmium, copper, nickel, and zinc—adversely affect fungi and bacteria such as actinomycetes, which serve as important forest tree symbionts.

Heavy-metal stress in forests, however, depends on both the concentration of metals in the soil and their biological availability. Heavy metals that cannot be readily exchanged from soil binding sites or are not in solution are unavailable for root or microbial uptake.

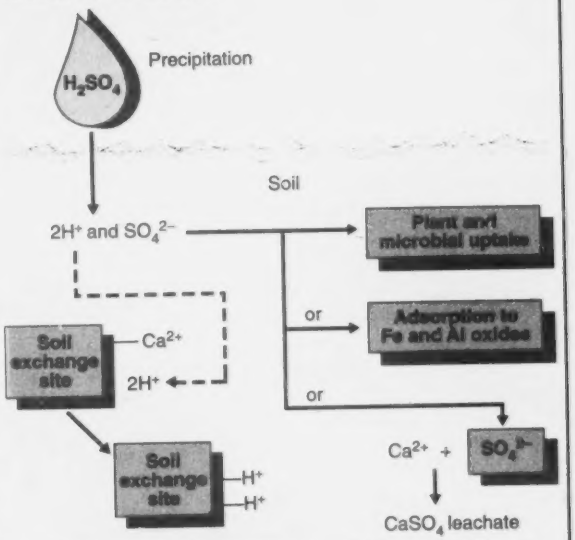
A number of processes make more than 90% of certain heavy metals deposited from the atmosphere biologically unavailable. They are adsorbed or chelated by organic acids, such as humic and fulvic acids; hydrous oxides of aluminum, iron, or manganese; and clays. Soluble cadmium, copper, and zinc may be chelated in excess of 99%. Heavy metals also form complexes with soluble low-molecular-weight compounds or precipitate as inorganic compounds of low solubility, such as oxides, phosphates, or sulfates. For example, William W. McFee, soil scientist at Purdue University, found that lead in a forest soil in northwestern Indiana is present in the following forms: bound to organic matter, 43%; bound to ferromanganese hydrous oxides, 39%; as insoluble precipitates, 10%; and biologically available (exchangeable), 8%. I hypothesize that the lead composition in many forest soils in the Northeast is similar.

Adsorption, chelation, and precipitation are strongly regulated by soil pH. As pH decreases and soils become more acid, heavy metals generally become more available for biological uptake, and concentrations that would not ordinarily be damaging may become so if the pH is low enough. Forest soils generally become more acid as they mature. However, especially in soils with a pH between 5 and 7, acid deposition from the atmosphere can increase the natural acidification process. Such acidification may make the heavy metals in the forest floor more available biologically.

In addition, the soil within about 2 mm of active roots—termed the rhizosphere—may also transform heavy metals from unavailable to available forms. Typically, rhizosphere soil has lower pH, lower water availability, lower osmotic potential, lower redox potential, and higher bulk density than soil away from roots. The rhizosphere processes of pH regulation, protonation, solubilization, reduction, and complexation may all transform unavailable metals to available ones. The pH of the rhizosphere and the availability of organic acids and phosphates may be particularly important in lead uptake.

Organic acids in the rhizosphere capable of complexing copper and zinc may be important in uptake of these metals by the roots. Reduction of manganese to the divalent form may allow greater uptake of this heavy metal. Complexing agents and the reduced pH in the rhizosphere may facilitate cadmium uptake. If rhizosphere processes are changed by acid deposition or oxidants from the atmosphere, the availability and uptake of heavy metals could be enhanced.

Sulfuric acid in precipitation leaches nutrients from soil



When sulfuric acid is deposited in soil by precipitation, nutrient cations can be leached from the rooting zone. Hydrogen ions from the acid may displace nutrient cations, such as Ca^{2+}, held on the negative faces of particles of clay or organic matter—called soil exchange sites—because the hydrogen ions have a higher propensity than calcium ions for attachment to the negative exchange sites. At the same time, the sulfate ion in the acid can follow three alternative pathways. It can be taken up as an essential nutrient by plants or soil microbes, it can be adsorbed to iron or aluminum oxides, or it can combine with the Ca^{2+} that is displaced by the hydrogen ion, and $CaSO_4$ can then leach from the rooting zone. If a sufficient amount of Ca^{2+} is not resupplied by decomposition of organic matter or soil weathering, forest trees may suffer from nutrient stress

Acid deposition

The oxidation of sulfur dioxide and nitrogen oxide emissions in the atmosphere ultimately produces sulfuric and nitric acids, which are deposited on the downwind landscape by both precipitation and dry processes. Sulfur dioxide is produced, among other ways, in the combustion of fossil fuels in coal-fired power plants and in the smelting of sulfur-rich ores. High-temperature combustion forms nitrogen oxides from nitrogen and oxygen: An important source is motor vehicle engines. Unless there is an unusual natural source of acidity, regional precipitation means of pH 5 or less are

Hypotheses propose effects of acid deposition on forest health

Over the past decade, a large number of hypotheses have been proposed to explain how acid deposition may interact with forest health. Most of them have focused on the increased levels of hydrogen, sulfate, and nitrate ions delivered through wet or dry deposition processes. The hypothesis that acid deposition leaches nutrients from soil horizons where roots are active and the proposal that acid deposition increases the biological availability of soil aluminum are receiving the most attention. But several other hypotheses form the basis of active study and experimentation. Some of these are listed here.

- Deposition adversely affects one or more processes of tree reproduction or seedling physiology.
- Deposition inhibits critical tree metabolic processes, such as photosynthesis, respiration, water uptake, or evapotranspiration.
- Deposition alters the allocation of carbon in trees, causing less of it to be stored or used for growth and more of it to be used for respiration and repair processes. Or acid deposition may result in an abnormal distribution of carbon between above-ground and below-ground tissues.
- Deposition increases or decreases microbial symbiotic relationships, such as those of mycorrhizal fungi and nitrogen-fixing bacteria.
- Deposition increases or decreases the activity of microbial pathogens.
- Increased deposition of nitrate and sulfate alters the dynamics of the nitrogen-sulfur cycle, including fertilization. Such disruption is particularly important because forest growth is commonly restricted by the availability of nitrogen.
- Deposition increases or decreases the activity of insect pests.
- Deposition increases or decreases the influence of abiotic stresses, such as temperature, moisture, and high winds.
- Increased input of hydrogen ions to the soil increases weathering rates for soil minerals and alters the availability of tree nutrient cations.
- Tree nutrient cations are leached from foliage tissues by precipitation that passes through the canopy.

generally the result of large anthropogenic emissions of sulfur and nitrogen oxides.

NAPAP is providing substantial details on the patterns of acid deposition in its "State of Science and Technology" reports. Its most complete monitoring results are for wet acid deposition, derived from six major networks that have been operating in North America for at least six years. Information for dry deposition, unfortunately, is much less complete because only two networks, using different procedures, have been monitoring it for only a few years.

The maximum deposition of sulfate and nitrate in precipitation occurs in the northeastern U.S. and southeastern Canada. The deposition locations have remained stable over the past 10 years. Currently, the mean annual pH of precipitation in the northeastern U.S. and in adjacent portions of Canada (also in North and Central Europe) is in the pH range of 3 to 5.5. Individual storms have been recorded with pH values between 2 and 3.

NAPAP's Mountain Cloud Chemistry Program, which ran five monitoring sites in the U.S., has characterized the chemistry of montane precipitation, which largely consists of cloud water (fog) that deposits on trees. Concentrations of H^+, SO_4^{2-}, NO_3^-, and NH_4^+ are 5 to 20 times higher in high-elevation cloud water than in nearby low-elevation precipitation, and cloud-water concentrations of SO_4^{2-} and NO_3^- at high elevations in the eastern U.S. are significantly greater than those in the western U.S. Therefore, the forests located above about 3000 feet along the Appalachian Mountain chain receive high doses of H^+, SO_4^{2-}, NO_3^-, and NH_4^+.

A large number of hypotheses about how acid deposition could affect forest health focus primarily on the greater than normal input of H^+, SO_4^{2-}, and NO_3^- ions delivered through wet or dry deposition processes. One that is receiving a great deal of attention now suggests that trees' nutrient cations are leached from soil horizons, where roots are actively taking up nutrients, to less active soil regions. Another proposes that acid deposition results in increased concentrations of biologically available soil aluminum. This causes roots to take up smaller quantities of nutrient cations or harms or kills fine roots or soil organisms.

To grow normally, trees require adequate supplies of 16 elements. Several of these—notably calcium, magnesium, and potassium—are taken up by tree roots as cations from aqueous solution in the soil. If this soil solution becomes depleted in nutrient cations, trees may be subject to nutrient deficiencies and, in turn, predisposed to additional damage from other stresses.

Nutrient leaching in soils requires additional cations to displace nutrient cations from soil exchange sites and mobile anions to combine with displaced cations for movement. The deposition of strong mineral acids from the atmosphere provides displacement cations in the form of hydrogen ions and mobile anions in the form of sulfate and nitrate ions. In most forest soils, rapid biological uptake may immobilize the nitrate anion, because most forests are nitrogen-limited. Similarly, sulfate anions may be immobilized in weathered soils by adsorption to free iron and aluminum oxides. In other soils, however, especially those low in free iron or aluminum oxides or high in organic matter (which appears to block sulfate absorption sites), sulfate may combine readily with nutrient cations and leach them beyond the rooting zone.

Field evidence of leaching induced by acid deposition comes from diverse forest ecosystems subject to excessive inputs of atmospheric acid and located in regions where the soils are vulnerable to anion migration. A. V. Mollitor and Dudley J. Raynal of the State University of New York, Syracuse, have provided evidence from northern hardwood and conifer stands near Newcomb in the Adirondack region of New York State; Christopher S. Cro-

nan, University of Maine, Orono, has obtained data from the subalpine conifer forests of Mount Moosilauke, N.H.; P. W. Hazlett and N. W. Foster, Great Lakes Forestry Centre, Forestry Canada, have provided evidence from the northern hardwood forest near Sault Ste. Marie, Ontario; and E. D. Schulze, Lehrstuhl Pflanzenökologie, Universität Bayreuth, Germany, has supplied information from the conifer forests of the Fichtelgebirge Mountain region in northeast Bavaria.

Aluminum, the third most abundant element in Earth's crust, occurs primarily in aluminosilicate minerals, most commonly as feldspars in metamorphic and igneous rocks and as clay minerals in weathered soils. Despite high concentrations of total aluminum in forest soils, aluminum does not usually interfere with nutrient uptake or cause biological toxicity, because it is tightly bound or is in insoluble form. However, when strong mineral acids are added to forest soils, they may mobilize aluminum by dissolving aluminum-containing minerals. They can also remobilize aluminum previously held on soil exchange sites or precipitated within the soil as the soil developed. If soil solutions become enriched in dissolved aluminum, principally as free ions (Al^{3+}) or as the monomeric hydroxides, $AlOH^{2+}$, $Al(OH)_2^+$, $Al(OH)_4^-$, the risks of aluminum interfering with nutrient cation uptake and of directly killing or harming roots and microbes is increased.

Walter C. Shortle and Kevin T. Smith of the USDA Forest Service in Durham, N.H., suggest that aluminum-induced calcium deficiency is important in the health and productivity of red spruce in the northeastern U.S. They collected tree cores, fine root samples, and soil samples at eight sites throughout northern New England. From their analyses of the cores, they found that calcium is incorporated at a constant rate per unit of wood volume throughout the life of trees and that demand for calcium increases as tree size increases. From chemical analyses of soil, they found that soil acidity levels at all the locations they tested were high enough to allow aluminum to exist in soluble forms in soil solutions. Their analyses of fine root samples found more aluminum than calcium at most sites. Shortle and Smith conclude, as have others, that when aluminum is more prevalent than calcium in the roots and other internal tissues of the tree, calcium is restricted because of competition between these cations for binding sites in tree root interiors. Reduced calcium uptake ultimately suppresses tree growth and may predispose trees to insect and disease attack.

A large integrated project called Aluminum in the Biosphere, sponsored by the Electric Power Research Institute (EPRI), Palo Alto, Calif., measured inorganic aluminum concentrations in many forest soils. In general, the highest available aluminum concentrations are associated with mineral (as opposed to organic) soil layers, where fewer than 10 to 15% of the soil exchange sites are occupied by nutrient cations, soil pH is less than 4.9, and the level of sulfate in the soil solution is greater than 80 micromoles per L.

The highest concentration of aluminum in the soil solution found in North America by the EPRI survey—about 1500 μg per L—was at the town of Big Moose in the Adirondack region of New York. The highest aluminum concentration overall was in the Sölling region, northeast of Bonn, in north central Germany, which had four times the concentration recorded at Big Moose. Available aluminum is directly toxic to trees at sufficient concentrations; specific thresholds vary by species. Its direct toxic effects in root tissues include reduced cell division resulting from aluminum binding to DNA, reduced root growth caused by inhibition of cell elongation, and destruction of epidermal and cortical cells.

The evidence generated by NAPAP and other integrated studies does not provide conclusive evidence that acid deposition has caused a general decline of forest health. However, NAPAP's report on changes in forest health and productivity does not rule out acid deposition "as a potential cause of future ... forest nutrition problems through effects on element cycling." Experimental evidence indicates that acid deposition and associated pollutants may make red spruce less resistant to winter injury and may have contributed to the dieback and mortality of red spruce at high elevations in the northern Appalachians, the report concludes.

Open-top chambers at the Institute for Ecosystem Studies at the Cary Arboretum in Millbrook, N.Y., are used to study the effect of ozone on forest tree growth. Saplings are grown inside the chambers, which consist of lightweight metal frames covered with plastic film. About 60 cubic meters of air per minute enters the chambers through a manifold in the lower section. The air entering the "control" chamber passes through particulate and charcoal filters to remove ozone and other contaminants. In the other chambers, different levels of ozone are achieved, either by adding ozone to the ambient air or by using various degrees of partial filtration to remove some of the ozone from ambient air

Oxidants

In sunlight, nitrogen dioxide dissociates in the troposphere (the portion of the atmosphere that extends outward about 7 to 10 miles from Earth's surface) and forms equal numbers of nitric oxide molecules and oxygen atoms. The oxygen atoms rapidly combine with molecular oxygen to form ozone. This ozone then reacts with nitric oxide, on a one-to-one basis, to re-form nitrogen dioxide. The steady-state concentration of ozone that is produced by this cycle is small. When hydrocarbons (from incomplete combustion in motor vehicles, for example), aldehydes, or other reactive atmospheric constituents are present, however, they form peroxy radicals that oxidize the nitric oxide back to nitrogen dioxide. With reduced nitric oxide available to react with ozone, the latter may accumulate to relatively high concentrations.

Numerous tropospheric oxidants, such as peroxyacetyl nitrate, nitric acid, and hydrogen peroxide, are toxic to vegetation. Ozone, however, is judged to be the most important atmospheric oxidant because of its elevated levels over vast regions of the U.S. and Canada during the growing season and its demonstrated importance for agricultural crops and forest tree health.

Because ozone can survive at significant concentrations for more than one day of transport, urban plumes are the major contributors to elevated tropospheric ozone concentrations at nonurban locations. According to EPA measurements, more than 100 urban areas in the U.S failed to meet the ambient air quality standard for ozone (120 ppb for daily maximum one-hour average, not to be exceeded more than once per year) during the late 1980s. Large areas of agricultural and forested land throughout the U.S. are exposed to ozone levels above the natural background level, which is 20 to 30 ppb. Ambient air over vast portions of eastern North America has an average ozone level of 50 to 70 ppb on clear summer days, with frequent peak concentrations of 80 to 110 ppb.

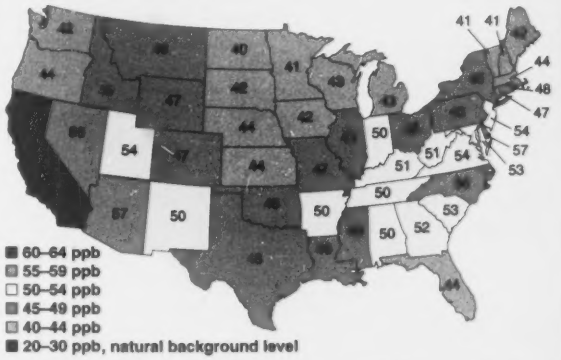
During the past decade, a number of organizations—including EPA through its National Dry Deposition Network and Storage & Retrieval of Aerometric Data programs, EPRI, the Tennessee Valley Authority, and the National Park Service—have monitored rural ozone. Allen S. Lefohn of A.S.L. & Associates, Helena, Mont., and John E. Pinkerton, National Council of the Paper Industry for Air & Stream Improvement, New York, have systematically reviewed rural ozone patterns in forested areas of the U.S. They conclude that elevated ozone concentrations can occur over very wide forested areas, with generally lower frequency in the Pacific Northwest, Upper Great Lakes, and northern New England and New York, and generally higher frequency in the Ohio River Valley and portions of Virginia, North Carolina, South Carolina, Georgia, Alabama, and Tennessee. Additional monitoring performed by states finds high ozone levels in southern New England, the mid-Atlantic states, and southern California.

Unlike heavy metals and acid deposition, whose adverse effects on forest ecosystems are generally long-term and caused by persistent accumulation or gradual process modification, ozone, a very reactive and highly unstable pollutant, interacts very rapidly with trees. For this reason, short-term, high-level ozone exposures are particularly important. But long-term, low exposures are also significant for more subtle adverse effects on plant health, such as yield reductions.

The specific stresses imposed on trees by ozone are extremely varied. The key hypotheses for ozone's adverse impacts on tree health are similar to those for acid deposition. Ozone influences tree reproductive processes, alters (both stimulates and restricts) insect and microbial pathogens of trees, and, at sufficient doses, destroys foliage and fine root tissues. By far, however, ozone affects forest tree metabolism most significantly by interfering with carbon dynamics, including photosynthesis, respiration, and carbon allocation.

Photosynthesis, the most fundamental metabolic process of trees, is the primary determinant of forest growth and biomass accumulation. In mature trees, net photosynthesis frequently takes up from 10 to 200 mg of carbon dioxide per g of dry weight per day. This extremely variable photosynthetic rate is influenced by genetic differences, season of the year, time of day, foliage position within the crown of the tree, age of foliage, solar radiation, climate, and soil factors. Unfortunately, air quality, particularly the ozone level, must also be added to this list. Evidence that ozone influences tree photosynthesis comes from a wide variety of sources ranging from studies of seedlings to large trees

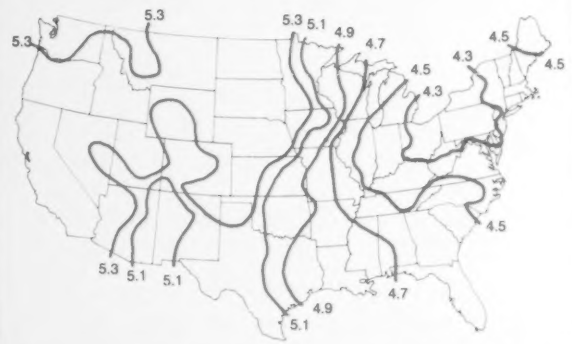
During the growing season, maximum tropospheric ozone levels are above natural background



Numbers represent the maximum seven-hour (9 AM to 4 PM) ozone concentrations in rural areas averaged by state from April to September in 1985–87. Ozone levels are highest on the West Coast and on the East Coast south of Pennsylvania. In all parts of the U.S., the concentrations are enough above the natural background level—20 to 30 ppb—to cause growth reductions in some vegetation. For some states where rural ozone is not monitored, a statistical strategy was used to extrapolate ozone measurements from areas where measurements are made to areas where none are made

Source: National Acid Precipitation Assessment Program

Mean precipitation pH is below 5 east of Mississippi River, above 5 west of it



The pH isopleths represent annual mean hydrogen ion concentrations expressed as pH and adjusted for the weight of precipitation in 1990. Levels below 5 east of the Mississippi River generally are the result of man-made emissions of sulfur and nitrogen oxides. A large number of coal-burning power plants producing huge quantities of sulfur dioxide in the Ohio River Valley cause the pH of precipitation to be especially low in that region and downwind from it

Source: National Atmospheric Deposition Program in the Natural Resource Ecology Laboratory at Colorado State University, Fort Collins, Colo.

and from experiments on trees growing in both controlled and natural environments.

Some of the most interesting and powerful evidence for ozone-induced alteration in carbon dynamics comes from studies employing "open-top chambers." These allow trees to be exposed to known levels of ozone in field (natural) environments. The chambers are cylinders or rectangles about 2.4 meters in diameter and 2.4 meters high constructed of lightweight metal frames covered with clear plastic film. They are equipped with blowers to introduce about 60 cubic meters of air per minute through a manifold surrounding the lower part of the chamber. The air entering "control" chambers passes through both particulate and charcoal filters. Nonfiltered chambers permit the use of ambient pollutants as a baseline for measuring the effect of additional exposures, which are obtained either by adding pollutants or by partial filtration to reduce the ambient pollution level.

Over the past decade, many investigators have employed field chambers to study the influence of ozone on both hardwood (oak, maple, poplar) and softwood (eastern white pine, ponderosa pine, southeastern pine) tree species. In most cases, they find ozone-induced changes in carbon dynamics lead to declines in growth or yield. In many experiments, these declines occurred in the absence of any visible symptoms of stress.

The National Crop Loss Assessment Program, a multiagency federal research effort, has found yield losses in many agricultural crops grown in areas where the seven-hour mean for ozone is 40 ppb during the growing season. Results for selected species of woody plants suggest forest trees may also grow less at the exposures that adversely affect agricultural species.

Peter B. Reich of the Boyce Thompson Institute for Plant Research in Ithaca, N.Y., reviewed the impact of ozone on plant photosynthesis and productivity. At low ozone levels (about 50 ppb), evidence from agricultural crops, hardwood trees, and conifers suggests that net photosynthesis and growth are reduced linearly as ozone uptake increases, he says. Agricultural crops are more sensitive than hardwoods, which in turn are more sensitive than conifers. Reich believes these differences in sensitivity result from several factors: Conifers generally take up less pollutant than crop species and require longer exposure to ozone to receive a comparable dose; conifer foliage is less productive per unit time than crop foliage; and conifer needles have a higher capacity to resist stresses, such as low supplies of nutrients or stresses from insects or microbes, than crop foliage. He thinks hardwoods lie between crop species and conifers in these properties.

Many studies suggest that photosynthesis and growth in agricultural crops decline significantly following one to two weeks of ozone at levels that are common in a typical growing season (50 to 70 ppb). Hardwoods show similar decreases after several additional weeks of elevated ozone concentrations. Effects for them begin when the integrated exposure (concentration × time) above background reaches about 10 to 20 ppm-hours. To show effects, conifers may need several months of elevated ozone concentrations resulting in integrated exposures of about 25 to 100 ppm-hours.

In addition to photosynthesis, the allocation and utilization of carbon within a plant is a critical regulator of plant health. Trees allocate carbon to a variety of processes including growth, respiration (energy generation for growth and tissue repair), metabolism, reproduction, and defensive chemicals to reduce insect attack or microbial infection. Exposure to ozone may influence this carbon allocation. Although all evidence is not consistent, several studies suggest that ozone exposure reduces the movement of carbon to roots. In trees, between 15 and 50% of the carbon fixed through photosynthesis is needed to produce, maintain, and replace fine root systems. A reduction in root growth resulting from a reduced supply of carbon could increase the risk of drought stress and could also exacerbate nutrient deficiencies.

Furthermore, a number of studies indicate that more carbon is allocated to respiration following ozone exposure. More carbon to respiration means less carbon is available to be stored as woody tissue. Similarly, reduced carbon allocation to the synthesis of defensive chemicals could allow more insects and pathogens to harm the tree.

I agree with Reich and his colleagues that the ambient concentrations of ozone that are common over vast areas of farm and forest land throughout the U.S. and southern Canada during the growing season (greater than 50 ppb) are probably sufficient to reduce photosynthesis or to perturb carbon dynamics, resulting in growth reductions of some vegetation.

Classic studies conducted in the San Bernardino National Forest in southern California provide evidence for both tree mortality and growth reduction caused by ozone. The position and elevation of the San Bernardino Mountains east of the Los Angeles Basin allows them to function as a barrier to the movement of marine air and facilitates the development of inversion layers in the Los Angeles Basin. Air pollutants trapped beneath the inversion layer are drawn into the forest at higher elevations by a "chimney effect," resulting from radiant heating on the south-facing slopes. As a result, the San Bernardino and Angeles national forests have the highest forest exposures to oxidants in North America (extreme episodic peaks of 300 to 400 ppb). Exposure to ozone gradually makes some of the needles on the trees in these forests yellow or pale (chlorotic), and eventually these needles fall off the trees. Finally, the trees may be killed by bark beetles or microbial root infection.

Among air contaminants, oxidants may have strongest impact on forests

Ecosystem component or process	Relative strength of evidence[a] Oxidants	Trace metals	Acid deposition
EFFECTS ON NUTRIENT CYCLING			
Increase nutrient availability			
Increase nutrient input	0	1	2
Increase soil weathering	0	0	1
Decrease nutrient availability			
Reduce litter decomposition	0	4	1
Increase soil acidification	0	0	2
Increased cation leaching from soil	0	0	3
Decrease microbial symbioses	1	3	0
Increase aluminum availability	0	0	3
EFFECTS ON PRIMARY PRODUCERS (TREES)			
Reproductive physiology			
Reduce flowering	1	1	0
Reduce pollen	1	0	0
Alter seed production and germination	1	1	1
Foliar physiology			
Reduce photosynthesis	4	1	0
Alter carbon allocation	3	0	0
Increase cation leaching	0	0	3
Increase necrosis	4	1	0
Root physiology			
Decrease water and nutrient uptake	0	1	2
Increase necrosis	1	1	2
Reduce tree growth	4	1	1
EFFECTS ON CONSUMERS OF TREES			
Insect pest activity			
Increase	4	0	0
Decrease	2	0	0
Microbial pathogen activity			
Increase	4	1	1
Decrease	2	2	0
Bird and mammal activity			
Reduce food	2	0	0
Reduce habitats	2	0	0
Increase morbidity and mortality	0	2	0
ALTER ECOSYSTEM SUCCESSION, SPECIES COMPOSITION, AND BIODIVERSITY	4	1	0
INCREASE OR DECREASE BIOMASS ACCUMULATION	4	0	0
TOTAL	44	21	22

a Evidence is scored on a scale of 0 to 4 according to its quantity and quality. A score of 0 means that evidence is very limited or that there is only a hypothesis. A score of 4 indicates that evidence is extensive and includes field data. Scores of 1,2, and 3 lie on a continuum between these two extremes.

Which air pollutant is most significant?

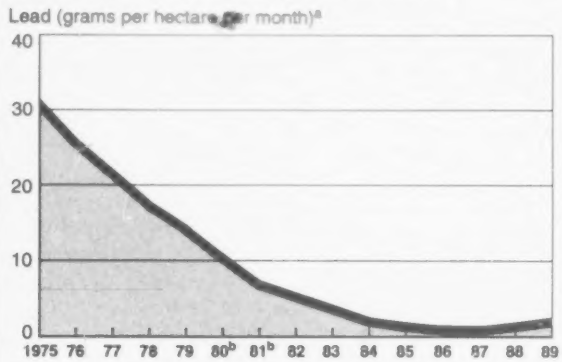
To decide which regional air pollutant is most important for forest health, three issues need to be considered: the strength of evidence linking adverse effects with typical pollutant exposures in large regions; the area of forest that is subject to significant deposition of each pollutant; and the probability of effective pollution management with regulatory strategies.

Many recent large research efforts, such as NAPAP; EPRI's Response of Plants to Interacting Stresses, Integrated Lake & Watershed Assessment Study, and Aluminum in the Biosphere programs; and the Air Quality/Forest Health Program of the National Council of the Paper Industry for Air & Stream Improvement have expanded understanding of the interaction between forest systems and air pollution. From the data generated by these efforts, a case can be made that ozone is the most significant regional contaminant. Moreover, a recent survey mailed to 41 North American forestry and air pollution specialists, chosen to represent a balance of expertise in this area, also found ozone to be the greatest threat to forest health.

In terms of the extent of U.S. rural landscape subject to deposition of regional pollutants, there is substantial evidence to rank them in the following order: ozone, heavy metals, and acid deposition. Rural monitoring shows elevated levels of ozone over wide areas of agricultural and forest regions. Because most heavy metals are associated with extremely fine particles in the troposphere and have very diverse and diffuse sources, they are also widely deposited over rural landscapes. NAPAP has clearly demonstrated that acid deposition is more region-specific because of the more concentrated distribution of primary emission sources, especially for sulfur dioxide in the Ohio River Valley, and the relative efficiency of certain deposition mechanisms, such as cloud-water deposition. As a result, even though the precipitation that falls over most of the U.S. east of the Mississippi has lower than natural pH (about 5.6), the greatest acid deposition occurs at high-elevation sites.

Reductions achieved thus far in regional air pollutants vary greatly according to source strengths, source distributions, available technologies, mitigation costs, and regulatory effectiveness. The requirement for electrostatic precipitators or baghouses on new industrial, utility, and incineration sources has greatly reduced heavy-metal emissions to the atmosphere. In addition, efforts to meet the ambient air quality standard for lead adopted in 1977, including the phase-down in the use

Lead deposition at Hubbard Brook forest has fallen dramatically since 1975



Note: Hubbard Brook Experimental Forest is located in White Mountain National Forest in central New Hampshire, relatively distant from any major local sources of lead. a Includes lead deposited in both wet and dry deposition. b Estimates.

of lead as a gasoline additive, has dramatically reduced the deposition of this toxin in rural landscapes.

In 1973, Yale University's Siccama and I initiated a detailed study of the biogeochemistry of selected heavy metals at the Hubbard Brook Experimental Forest in the White Mountain National Forest in central New Hampshire. This forest is about 70 miles northwest of Boston and relatively distant from any major local sources of heavy-metal emissions. We currently have 15 years of data on the inputs of pollutants from precipitation and dry fallout and the amounts of cadmium, copper, iron, lead, manganese, nickel, and zinc carried away by streams. Over the first 10 years of our study, the amount of lead deposited in our northern hardwood forest was greater than for any other metal pollutant. Lead inputs, however, have declined dramatically since the project began. This decrease correlates extremely well with the decrease in lead concentrations measured in ambient air in urban locations and with the decrease in lead consumed in gasoline over the same period.

The 1990 revisions to the Clean Air Act hold great promise to reduce the precursors of acid deposition over the next decade. The revisions call for a 10 million ton reduction in sulfur dioxide emissions and more than a 2 million ton reduction in nitrogen oxide emissions by 2000. After 2000, sulfur dioxide emissions will be capped, and no increase in total emissions will be allowed.

The ability of the revised Clean Air Act to achieve these high expectations regarding sulfur and nitrogen oxide emissions, however, will be realized only if the rules adopted are fully consistent with the original goals of the act. Some observers believe the regulations now being written by EPA and revised by the White House Council on Competitiveness will, in some cases, allow industrial facilities to increase their emissions of nitrogen oxides when they install scrubbers to remove sulfur dioxide. If so, the overall decrease in the emissions that cause acid deposition will not be so great as those achieved by the scrubbers alone.

The principal precursors for ozone synthesis—nitrogen oxides and hydrocarbons—are also specifically addressed in the revisions to the Clean Air Act. The 1990 act tightens emission standards for cars and trucks, requires reformulated gasoline in certain high-impact areas, and requires fleet operations in designated areas to use unconventional fuels, such as methanol, that are cleaner burning and give off smaller quantities of hydrocarbons.

Alvin L. Alm of Science Applications International in Bedford, Mass., expresses caution, however, regarding the ability of the revised act to bring about compliance with the ambient standards for ozone in the near term. He emphasizes that the stricter emission limits and use of unconventional fuels will help, but uncertainties about specific emission reductions and timetables and the shift of primary responsibility for compliance to the states may make compliance problematic. Thus, I predict ozone is the most significant regional air pollutant that poses risks to the future health of U.S. and Canadian forests.

The future

Intense research efforts of the past 15 years concerning the interaction of air contaminants with forests has taught us a great deal. However, definitive research on forests in the future will continue to be plagued by the following difficulties and limitations:

- Our forests are vast in size, highly variable, and valued for very different reasons by different people; therefore, it is difficult to quantify the extent or the economic losses caused by air pollution damage to forests.
- The subtle perturbations of 10 to 15% in ecosystem-scale processes caused by air pollution in North America are extremely difficult to measure or to separate from perturbations caused by other natural or unnatural stresses.
- Three- to five-year research programs, often funded by the federal government, cannot adequately document forest changes occurring over many decades.
- The subtle stresses regional air pollutants impose on forest ecosystems are not independent of one another or of other stresses and, in fact, are highly interactive.

To effectively address these problems and limitations, efforts must be expanded in two critically important areas—research and monitoring. It must be fully recognized that the applied science of forest health management depends directly on a basic understanding of tree and forest form and function. Greater fundamental understanding of tree biochemistry and physiology is desperately needed.

Further, we, as a society, need more appreciation of basic forest ecology and ecosystem dynamics. Research programs dedicated to specific stress factors must have both field and laboratory components. Studies of mechanisms of disease obtained in laboratories, growth chambers, and greenhouses must be combined with studies conducted in the field to obtain a comprehensive perspective. Efforts in controlled and natural environments must receive equivalent support and encouragement.

In addition, long-term, ecosystem-scale research must be encouraged and supported. Research information

must be synthesized and integrated in order to develop models of risk processes and to formulate management options. Predictions of ecosystem toxicology and stress processes must be provided to resource managers, regulators, and decisionmakers.

At the same time, governments must implement a comprehensive environmental monitoring program that will generate accurate information on the deposition of air pollutants in rural areas and that will allow changes in natural ecosystems to be assessed. Air quality monitoring is critical for accurately determining ecosystem exposure and for assessing the efficacy of pollution reduction strategies.

In addition, monitoring ecosystem change is essential to improve understanding of the dynamic nature of complex systems and to correlate change with environmental stress. Separating the effects of chemical pollutants from the effects of changing climate on trees needs to be addressed in monitoring programs. And documenting changes in the pattern of natural landscapes is critically important in order to differentiate natural stresses from man-made ones.

The objectives of the Environmental Monitoring & Assessment Program, a new initiative of EPA, are fully consistent with this need. They include estimating the current status, extent, changes, and trends in indicators of the condition of U.S. ecological resources; tracking indicators of pollutant exposure and habitat condition so as to reveal associations between human-induced stresses and ecological condition; and compiling periodic reports on ecological status and trends.

Regional air pollution is one of the significant contemporary anthropogenic stresses imposed on some temperate forest ecosystems. Gradual and subtle changes in forest metabolism and composition over wide areas, rather than dramatic destruction in the immediate vicinity of point sources over short periods, must be recognized as the primary consequence of regional air pollution in the U.S. and Canada. Global air pollution, including pollution from "greenhouse" trace gases, with its capability to alter fundamental radiation balances of Earth and potential to cause rapid climate change, could also dramatically alter forest ecosystems in the next century (C&EN, March 13, 1989, page 25).

The integrity, productivity, and value of forest and other wild systems are intimately linked to air quality. We must elevate considerations of environmental health to the same level as concerns for human health. Failure to take forest resources into account in considering energy technologies or in the management and regulation of air resources is shortsighted, for it fails to recognize the critical link between the quality of human experience and the quality of our environment. □

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